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An Analysis of Satellite Imagery in the Grand Banks Region

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Abstract

Isenor, A. 1988. An Analysis of Satellite Imagery in the Grand Banks Region. Can. Tech. Rep. Hydrogr. Ocean Sci. No. 111: iv + 62 pp.

An analysis of the available NOAA satellite imagery for the area defined by $41-51°$ N and $43-56°$ W is presented. The analysis uses 97 images collected over the period 1984–86 to produce monthly sea surface temperature (SST) statistics in 1° by 1° squares. The statistics include the minimum, maximum, mean and the standard deviation. The Labrador Current is clearly visible in the mean SST field. However, exchange information could not be determined using the standard deviation field.

The mean position of the Labrador Current, as defined by its cold SST manifestation, is also determined using 15 independent images of the Current. The mean position is then compared with imagery available from November 1985 which show the SST Current displaced by $O(50km)$ shelfward. The displacement is shown to be $O(2)$ standard deviations from the mean SST Current position.

Résumé

Isenor, A. 1988. An Analysis of Satellite Imagery in the Grand Banks Region. Can. Tech. Rep. Hydrogr. Ocean Sci. No. 111: iv + 62 pp.

L'auteur présente une analyse des images disponibles de la NOAA obtenues par satellite pour le secteur délimité par les latitudes 41 à 56°N et les longitudes 43 à 56°O. L'analyse fait appel à 97 images obtenues au cours de la période allant de 1984 à 1986 afin de produire des statistiques mensuelles sur la température de la mer en surface (TMS) dans des carrés de 1° par 1°. Les statistiques comprennent la valeur minimale, la valeur maximale, la moyenne et l'écart-type. Le courant du Labrador est clairement visible dans le champ des valeurs moyennes de TMS. Cependant, il a été impossible de déterminer les valeurs des échanges en se servant du champ des écarts-types.

L'auteur détermine également la position moyenne du courant du Labrador, telle que définie par sa manifestation de TMS froides, en se servant de 15 images indépendantes du courant. La position moyenne est ensuite comparée aux images disponibles obtenues en novembre 1985 qui montrent un déplacement du courant TMS de $O(50km)$ en direction de la plate-forme. L'auteur montre que le déplacement est de $O(2)$ écarts-types par rapport à la position moyenne du courant TMS.

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INTRODUCTION

The National Oceanic and Atmospheric Administration (NOAA) satellite images of the Grand Banks of Newfoundland have been evaluated, processed and analyzed for the period 1984–1986. The work consisted of evaluation of all slides available through the image processing centre at BIO to determine which passes should be considered in more detail. A list of these passes constitute the Quick Look Catalogue.

The passes indicated in the Quick Look Catalogue were then processed using the MIAMI software package at BIO. Those images which showed a portion of the Bank cloud free were noted and photographed. This short list with photographs is termed the Processed Image Catalogue.

The resulting image data base was then used to determine temperature statistics across the Bank. Temperature variance over the Bank was also investigated. As well, the position of the surface temperature manifestation of the Labrador Current was defined. One anomalous event was considered briefly.

This report outlines some of the work carried out this past year at the Bedford Institute of Oceanography which was made possible through the financial support of the Office of Energy Research and Development (OERD) of the Department of Energy, Mines and Resources. It, along with a catalogue of processed images delivered to the Coastal Oceanography Division, Physical and Chemical Sciences Branch, Department of Fisheries and Oceans, fulfills the requirements of a contract issued to Dalhousie University by the Department of Supply and Services. The statement of work of that contract is given in Appendix 1.

The following section describes the data base used. A discussion of the procedure used to determine the sea surface temperature (hereafter SST) statistics follows. A brief section on variance induced by trends is also given, followed by the presentation of the monthly SST statistics and a comparison of these statistics with other sources. A brief discussion on the monthly statistics is also given. Finally, the

method for determining the SST Current boundary using the imagery is presented. The mean SST Current position and an anomalous event are then discussed.

DATA AVAILABILITY

The NOAA imagery for the Grand Banks, shown in figure 1, are available approximately once per day. Thus, the 3 year study period represents a potential data base of about 1000 images. From these 1000, 230 were identified in the Quick Look Catalogue and processed. From the 230, 132 were dismissed as containing excessive amounts of cloud, thus resulting in 98 being photographed for the Processed Image Catalogue. Of these 98, 75 were obtained from NOAA 9, 1 from NOAA 8, 21 from NOAA 7 and 1 from NOAA 6.

The NOAA 7 and 9 imagery, which combine to account for 96 of the 98 images, both receive data in 5 frequency bands or channels. Channels 4 and 5 are in the infrared (IR) window and contribute to the processed IR field. Channel 3, which degrades through time, was not used in this study. Channels 1 and 2 represent the visible and visible/near IR windows, respectively. For the cloud determination in this study, channel 2 is used exclusively. Channel 2 is better suited for cloud detection because of the higher absorption coefficient of water in this band and also because of the reduced Rayleigh scattering (Maul, 1985).

Of the 98 images in the Processed Image Catalogue, 97 will be used in this study. One, on October 31 1984, has been omitted because of large nadir angle reducing resolution. These 97 images cover 94 days. There are 21, 30 and 46 images available in the years 1984–86 respectively. Of the 97, 4 do not have any channel 1 or 2 data. The image dates are listed by month and year in table 1. The complete Quick Look and Processed Image Catalogues are available in the OERD Library at BIO.

Processing, with the same center position (45.9° N, 49.5° W) and resolution ($2km$), was carried out on 90 of the 98 images. Thus, these 90 can be compared directly. As an avenue for comparison, a visual examination of the 90 images was

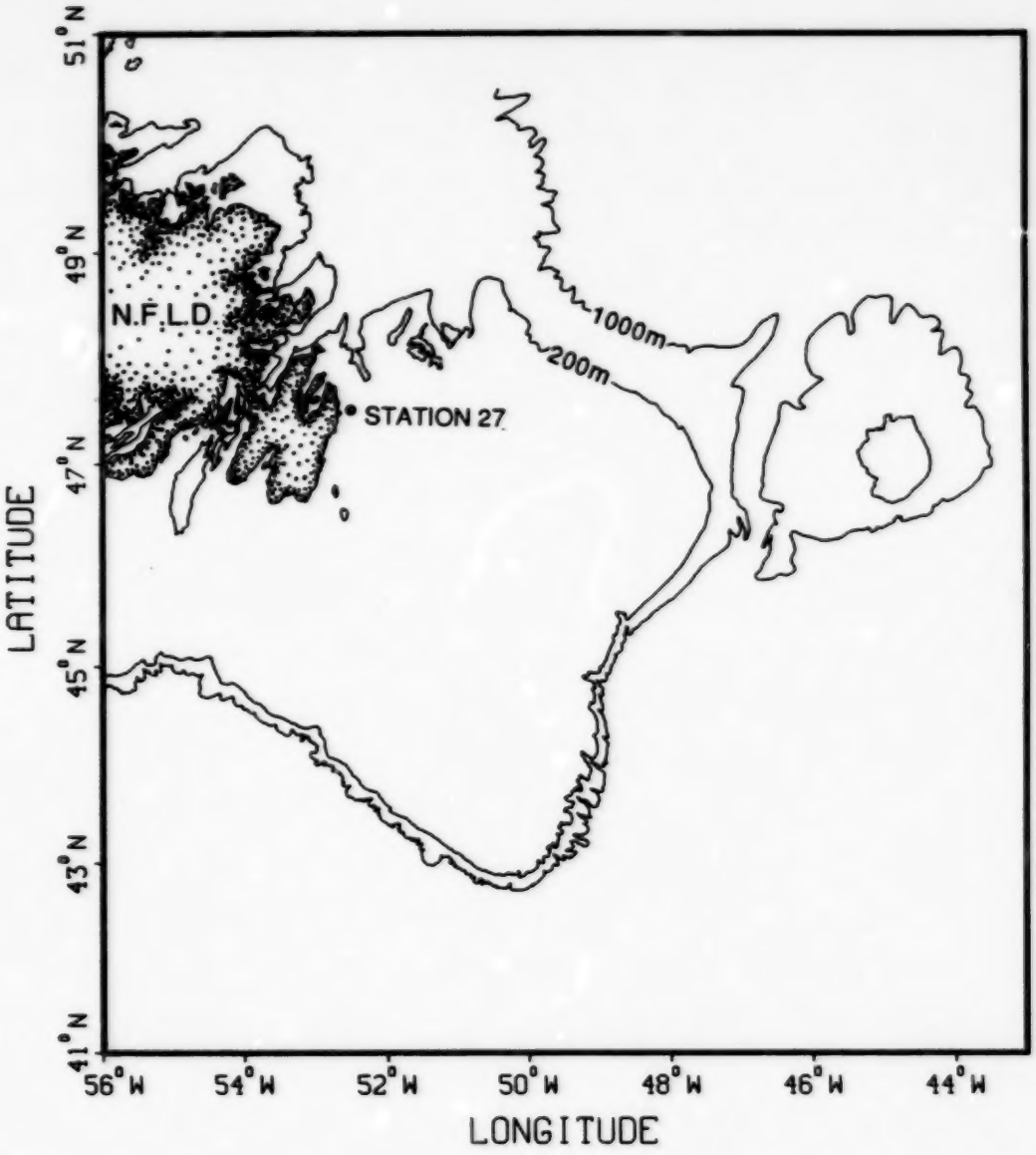

Figure 1: The study area showing Newfoundland, the 200 and 1000m isobaths, and Station 27.

Table 1: Complete list of image dates ordered by month and year. A "*" indicates 2 images on that day. Numbers following the year indicate dates for that month, in that year.

January	:	1986 - 12,13,19,29
February	:	1984 - 3 1986 - 27
March	:	1986 - 19,23
April	:	1984 - 2,5 1986 - 1,4,9,14,30
May	:	1984 - 4,11 1986 - 14,15*,16*,17
June	:	1984 - 6,25*,26,27,28 1985 - 16,21 1986 - 7,10,13,20,22,28
July	:	1984 - 14,26 1985 - 2,5,10,14,18,29,31 1986 - 2,18,24
August	:	1984 - 4,10,16,23,26 1985 - 3,5,19,26 1986 - 6,13,14,17,27,29,31
September	:	1984 - 26 1985 - 2,15,18,19,22,23,29 1986 - 10,16,19
October	:	1984 - 5,31* 1985 - 4,5,6,9,17 1986 - 8,9,21,26
November	:	1985 - 4,5,12 1986 - 2,8,11
December	:	1985 - 1,31 1986 - 17,19

carried out and the cloud free area estimated. Due to the subjective nature of the method, the estimates are to the nearest 10%. The histogram of the number of images in each 10% interval is shown in figure 2.

PROCEDURE FOR DETERMINING SST STATISTICS

A recent analysis by Drinkwater and Trites (1986a) (hereafter DTa) gives monthly means and standard deviations for temperature in various subareas on and around the Grand Banks of Newfoundland as determined from archived data. The temperature data, primarily measured by reversing thermometer, cover the years 1910–1982, with 85% of the data after 1950. The spatial resolution of satellite IR imagery makes a similar analysis for the surface an obvious step.

For the present study attention is focused on the Grand Banks and particularly its interaction with the Labrador Current. Considering this in conjunction with a topographic map including lines of latitude and longitude (figure 3) one may consider as a first step, subareas which are defined as $1° \times 1°$. Such subareas were chosen because they are completely arbitrary and resolve the topography of the Bank reasonably well. These subareas will also encompass eddies in the area which are estimated to have a diameter of $20 - 40km$ (Petrie and Isenor, 1985).

Before analysis begins, several decisions must be made with regard to the imagery data base. One such decision deals with the spatial resolution of the imagery. The maximum resolution obtainable using the NOAA series of satellites is $1km$. However, processing can reduce this resolution to $2km$, allowing the processed area to quadruple. To determine what information is lost when using the $2km$ resolution image, the minimum, maximum, mean and standard deviation in the temperature field were calculated within each $1° \times 1°$ subarea for an image on October 31, 1984. The mean statistic for all subareas was then calculated (see table 2). One notes that the maximum difference between any pair is 0.22° C, well within the quoted sensor accuracy of 0.6° C noted by others (Llewellyn-Jones *et al.* 1984, McClain *et al.* 1985, and Schluessal *et al.* 1987). We conclude that processing at $2km$ resolution

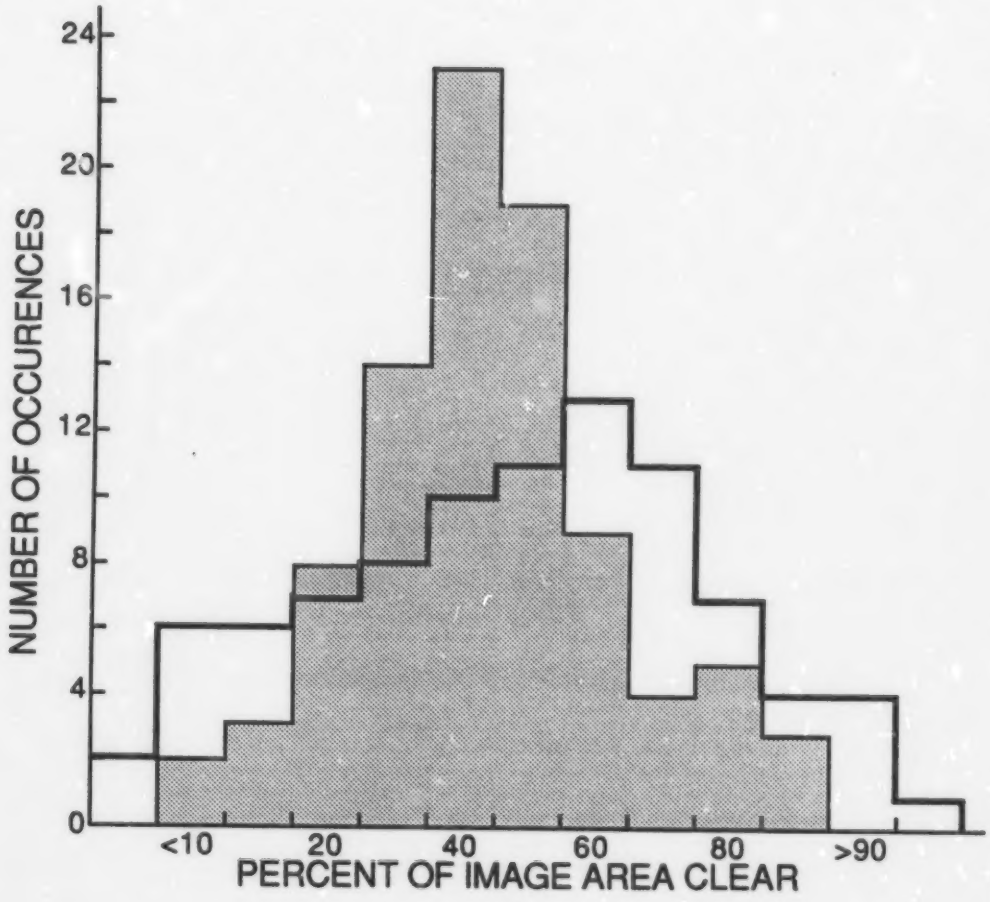

Figure 2: Histogram showing the percentage of area clear defined by 56 - 43° W and 51 - 41° N (shaded area) and percentage of the Grand Banks clear defined by the 200m isobath (solid line).

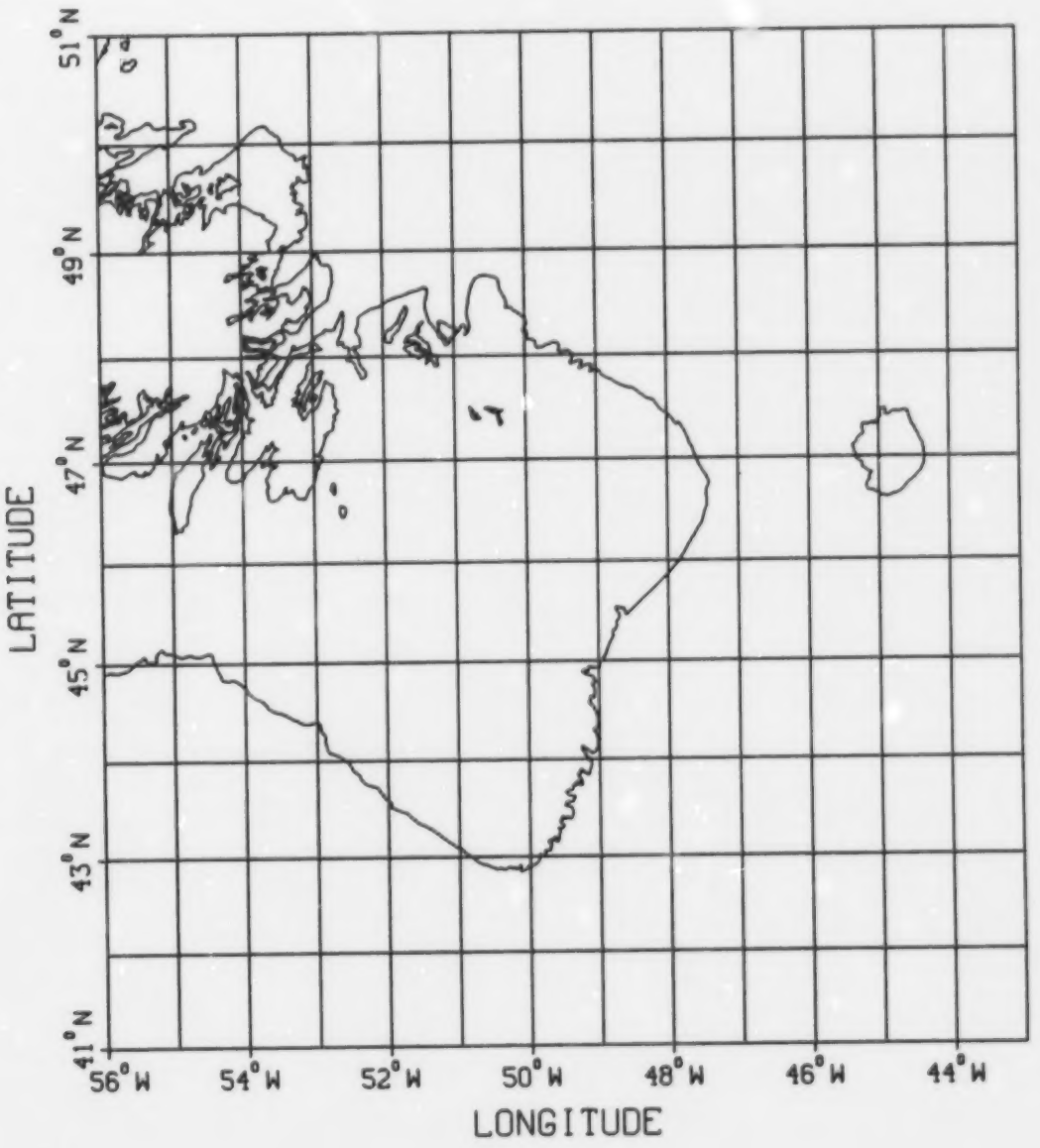

Figure 3: The study area showing Newfoundland, the 200m isobath and the $1° \times 1°$ grid.

Table 2: Comparison of October 31,1984 image processed at $2km$ vs. $1km$ resolution. Values indicate the mean (note overbar) of each statistic as determined from 20 subareas of 1° × 1°. Units are ° C.

	min	max	mean	std. dev.
$2km$	3.76	10.07	7.03	1.27
$1km$	3.56	10.29	7.02	1.31
difference	0.2	-0.22	0.01	-0.04

Table 3: Comparison of the October 31, 1984 image with a 3 × 3 median filter applied and with no filter applied. The image was processed at $2km$. Values indicate the mean (note overbar) of each statistic as determined from 77 subareas of 1° × 1°. Units are ° C.

	min	max	mean	std. dev.
filtered	2.45	10.09	6.09	1.66
unfiltered	1.89	10.98	6.11	1.88
difference	0.56	-0.89	-0.02	-0.22

will not introduce errors above the sensors accuracy and thus is acceptable for the present study.

Another decision deals with the application of a filter. Applying a median filter to the image results in a smoothed thermal field which could alter the statistics. As a comparison, statistics were computed using 77 $1° \times 1°$ subareas in a $2km$ resolution image of October 31 1984, both filtered and unfiltered (see table 3). Results indicate changes in the filtered minimum and maximum on the order of 0.8° C, slightly above the quoted accuracy of the sensor. However, the changes in the mean and standard deviation are below the quoted accuracy. This, combined with the knowledge that such small scale filtering will maintain linear features of scales $> 1 \times 3$ pixels, suggests that the application of such a filter is desirable.

As with all oceanographic applications of satellite IR imagery, the atmosphere presents a challenge. For this study, attempts to distinguish cloud from water concentrated on cloud in the visible/near IR channel 2. The user specifies an acceptable radiance range (specified in pixel values) for the channel 2 image. This range represents the radiance of the ocean. The algorithm then examines two pixels corresponding to the same position, one each from the near IR and IR images. The IR pixel is considered to represent a water temperature if the visible/near IR pixel is within the specified radiance range. Although this radiance range should be based on a histogram of the channel 2 image, for this study the author will subjectively determine the range.

A land discrimination mechanism was also included as a means of eliminating the influence of land pixels. The land discrimination uses a graphic mask which is easily applied using the MIAMI system. Consequently, the resulting statistics will be indicative of water only. The accuracy of the land mask is the accuracy of the navigation, which is $\pm 1km$.

CONTAMINATION TO THE VARIANCE FIELD

One goal of this study is to determine areas of preferred exchange using the temperature variance field. Thus, interest lies in the variance induced by eddies, etc. along the Bank edge. Variance induced from other features, such as trends or fronts, must therefore be identified, as these features represent a source of contamination to the required variance field. These features will now be considered.

As an estimate of the induced variance in the $1° \times 1°$ subareas, consider the large scale annual temperature gradient. An estimate of the annual gradient in the east-west direction may be obtained from Drinkwater and Trites (1986b) (hereafter DTb), where a brief overview of environmental conditions in the Northwest Atlantic is presented. Considering the annual mean temperature in each area given by DTb as determined from the 1972-80 data base, we find the Bank can be described by an annual gradient in temperature of 0.7° C/degree longitude.

To estimate the north-south gradient consider the mean surface temperatures presented by Templeman (1975). The mean values, calculated from data obtained in the months of July and August for the years 1951-71, are seasonally biased. However, they still represent a suitable data base for an estimate of the temperature gradient. Although Templeman (1975) does not describe a transect in the north-south direction, 4 stations from 4 different sections can be combined to yield a north-south gradient estimate along 50 W of 1.6° C/degree latitude. The St. John's–Flemish Cap section along 47°N can also be used to obtain an estimate of the east-west gradient. Using the data from 51 to 47.5° W, one obtains an east-west gradient of 0.5° C/degree longitude, in reasonable agreement with the estimate from DTb.

As a final estimate of the annual north-south gradient, consider DTa. Although the large subareas over the Bank make the comparison difficult, an estimate of the annual north-south gradient can be obtained by comparing the mean temperature

for each month from subareas 20 and 21, and also 19 and 22. Both comparisons yield a north-south gradient of $\sim 1°$ C/degree latitude.

Thus, the 3 estimates of the north-south temperature gradient are 1.6, 1, and 1° C/degree latitude and the east-west estimates are 0.5 and 0.7° C/degree longitude. Consider 1.4 and 0.7° C/degree as representative of the two annual gradients in the north-south and east-west directions respectively. Applying these gradients one can determine the induced variance in a $1° \times 1°$ subarea to be $0.25° C^2$, or an induced standard deviation of 0.5° C.

The above calculation deals with the annual mean gradient in the temperature field. However, with a strong seasonal cycle, one should also briefly consider the monthly variation. Thus, again consider DTa subareas 20,21 and 19,22. One can use these subareas to calculate the maximum monthly north-south gradient of $\sim 2°$ C/degree latitude. For comparison, a north-south gradient of 2° C/degree latitude and an east-west gradient of 0.7° C/degree longitude will produce a standard deviation in the temperature field of about 0.6° C.

The variance introduced by the presence of a strong front should also be examined. Thus, consider a $1° \times 1°$ cell with a sharp temperature front running north-south in the centre of the cell. Assume the front separates water masses which differ in temperature by 3° C. Superimpose on this the annual gradient (1.4 and 0.7° C / degree). The resulting standard deviation in the temperature field is 1.4° C.

For a final comparison, consider the variance introduced by an eddy. Assume a single eddy, with radius $24km$, located in a $1° \times 1°$ cell. Assume the temperature difference between the eddy and the background water is 3° C. Again superimpose the annual mean gradient. The resulting standard deviation in the temperature field is 1.3° C.

To summarize, the mean annual gradient has been estimated at 1.4° C/degree latitude and 0.7° C/degree longitude. This gradient will produce a standard deviation of 0.5° C. Monthly variations do not alter this value significantly. A front,

typical of the Labrador Current/shelf water boundary, superimposed on the annual gradient, can result in a standard deviation of 1.4° C. Finally, a $48km$ diameter eddy superimposed on the annual gradient will produce a standard deviation of 1.3° C. Thus, we see a potential problem with determining the location of exchange due to eddies. A sharp Labrador Current/shelf water boundary can in fact produce a standard deviation in the temperature field of the same order as an eddy.

MONTHLY SST STATISTICS

The results of the monthly SST statistical calculation are now presented. The six values which appear in each subarea and the monthly statistics are displayed in Appendix 2. The six values in each subarea, in order from top to bottom, are the number of images used, the percentage of points, the mean temperature, standard deviation of the temperature, the minimum temperature and the maximum temperature. The "number of images" refers to the number of images which contributed values of SST to that particular subarea. The "percentage of points" refers to the number of pixels used in the calculation for that subarea compared to the total number available. Both values can be used as an indicator of the representativeness of the subsequent values. These values can also be used to obtain an estimate of the number of points used in the calculation, knowing that for each subarea in open water, one image will contribute a maximum of 1950 pixels of SST. Also in Appendix 2 are contour plots of the mean SST field and standard deviation field. A list of image dates used in the statistical calculation is given in table 1.

As noted previously, the mean monthly statistics are based on the available imagery over the period 1984 - 86. In comparison to the DTa time period (72 years), this is very brief. One should therefore consider the representativeness of this time period for determining the given statistics.

A recent analysis by Petrie *et al.* (1988) considered the Station 27 (47°33'N, 52°35'W; see figure 1) temperature data with particular emphasis on the 1984 - 86

time period. Their analysis showed that this was a period of below normal temperatures at virtually all measurement depths. At the surface, the mean anomaly was −0.5° C over this period. This indicates that the period of calculation for these statistics may not be completely representative of normal conditions.

SST COMPARISON

Obviously, the first question which must be addressed with these statistics deals with the representativeness of the data and errors associated with the resulting values. As noted above, 1984 - 86 may be a period of below normal temperatures, thus biasing the mean values low. This will now be investigated.

The most extensive data base of bulk near surface temperature is from ship-of-opportunity measurements. However, several problems exist when comparing satellite and ship temperature measurements. For example, a ship obtains individual point measurements while a satellite radiometer obtains instantaneous surface averaged measurements. However, using the monthly mean temperatures for a given area reduces this problem as now the ship observations also represent a spatial average. This increases the statistical significance of the mean values and given adequate coverage, should reduce the mean difference between the 2 data sets as compared to individual point comparisons. Ship data may also be biased high (Tabata, 1978), however, this is not a serious problem.

The afternoon effect (Bernstein and Chelton 1985), which is near surface solar heating, can create large differences between ship and satellite temperature measurements. This effect has been noted by others examining near surface temperature records from anchored buoys on the Bank (Loder and Ross, 1988). The potential differences are typically a few °C. Thus, this effect is considered the dominant influence on the IR data. We therefore predict that the IR data will be biased high compared to other observations.

As an initial comparison of satellite and ship temperature data consider the monthly mean SST's with those monthly means from a Canadian Climate Program

(1984) report dealing with the climatology of the east coast of Canada. Computing the mean monthly temperature over the area defined as the "Grand Bank" from the means in the subareas results in 12 mean monthly values which can be compared with the corresponding 12 climatological values. Figure 4 gives the comparison of SSTs and indicates that the mean absolute temperature difference and the root mean square temperature difference are 0.8° C and 0.9° C respectively, for the 12 months. This is considered to be excellent overall agreement.

Another comparison of the IR monthly statistics and those from the literature can be made using DTa. Consider the DTa subarea #20, located in the northeastern Grand Bank. Overall, we again see very good agreement between the data sets (figure 5) with the mean absolute temperature difference and the root mean square difference between the two estimates being 1.6 and 1.8° C respectively. Of the 3 DTa subareas considered, the largest differences occured in subarea #20.

Also shown in figure 5 are the monthly standard deviations from the two data sets. We see that the magnitude of the standard deviations agree reasonably well. For this comparison, the mean absolute difference in the standard deviations is 0.5° C.

Although previous literature provided the mean and standard deviation of temperature, the single measurement maximum or minimum temperatures were not presented. In the monthly statistics from the IR imagery, such values are included. However, these statistics must be viewed with much discretion as they represent the largest or smallest single pixel value for the subarea and, therefore, are not statistically reliable.

A serious problem with the minimum values is the influence of undetected cloud. An example of this appears in the southeastern most subarea in the August map (see Appendix 2). The subarea, centered at 41.5° N 43.5° W, is in the area influenced by the Gulf Stream. However, the minimum temperature is given as 3.4° C. The surrounding 3 subareas have a mean minimum temperature of 13° C,

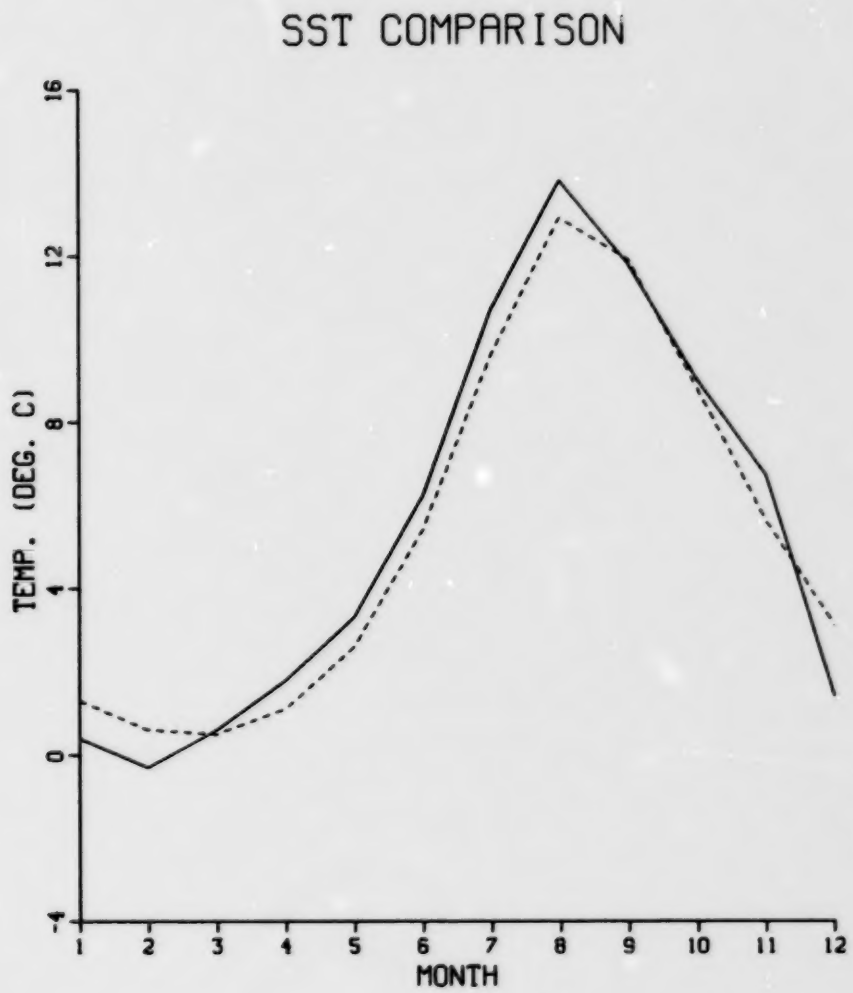

Figure 4: SST comparison. Solid line represents IR temperature, dashed line represents temperature obtained from Canadian Climate (1984) report on the climatology of the east coast. Months are referenced by number with January being 1. Standard deviations were not given in the Canadian Climate (1984) report.

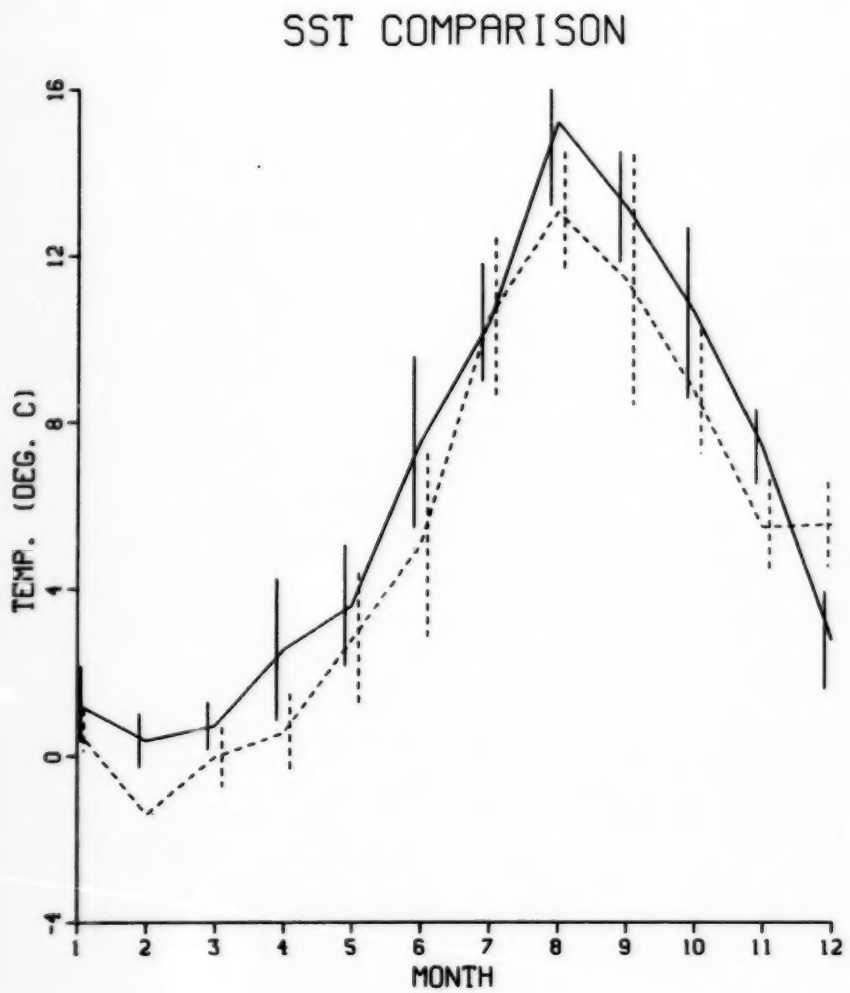

Figure 5: SST comparison. Solid line represents IR temperature, dashed line represents temperature obtained from DTa subarea 20. Months are referenced by number with January being 1. The vertical lines represent ±1 standard deviation for each month from the two data sources. The vertical lines are offset for clarity.

indicating the presence of the warm Gulf Stream. The 3.4° C minimum is unrealistically low because of cloud which escaped detection in the statistical algorithm and reduced the temperature of at least one pixel. However, the effects of this cloud on the mean of that subarea is low, as can be seen by comparing the mean from that subarea, 23.7° C, with the means from the 3 neighbouring subareas 22.9, 22.9 and 23.5° C. Perhaps a better indicator of the lower and upper temperature limit would be the mean ± 2 standard deviations.

DISCUSSION OF SST FEATURES

The monthly SST maps represent an enormous amount of data. Each $1° \times 1°$ subarea has an average of 4 images per month with $\sim 75\%$ coverage which amounts to O(6000) temperature estimates per subarea. The data base, condensed into the monthly maps or into a single map based on the mean of the monthly statistics (the annual map, see figures 6 and 7), can now be used to identify various oceanographic features in the area of the Grand Bank.

With regards to the Grand Bank, the most important oceanographic feature is the Labrador Current. The Current is visible in the mean temperature field in all of the monthly maps (Appendix 2) and therefore appears in the annual map as well. The Labrador Current signature is a reduction of the mean temperature in the subareas at or near the $200m$ isobath. In some monthly maps this reduced mean can be traced from the northern edge of the study area to 41° N, a distance of $1000km$.

Although the Labrador Current is visible as a subarea of reduced SST along the Bank edge, the actual mean temperature given for the subareas influenced by the Current can be expected to be an overestimate of the SST of the Current itself. The Current is $\sim 50km$ wide (see Petrie in Benoit and Mungall, 1983) and since the resolution of the $1° \times 1°$ grid is at best $75km$, the mean temperatures would include measurements from either side of the Current, thereby increasing the mean.

Figure 6: Legend for the annual map (figure 7). The 4 values in each subarea correspond to the following:

total number of images

average percentage of points

average of the 12 mean temperatures (° C)

average of the 12 standard deviations in temperature (° C)

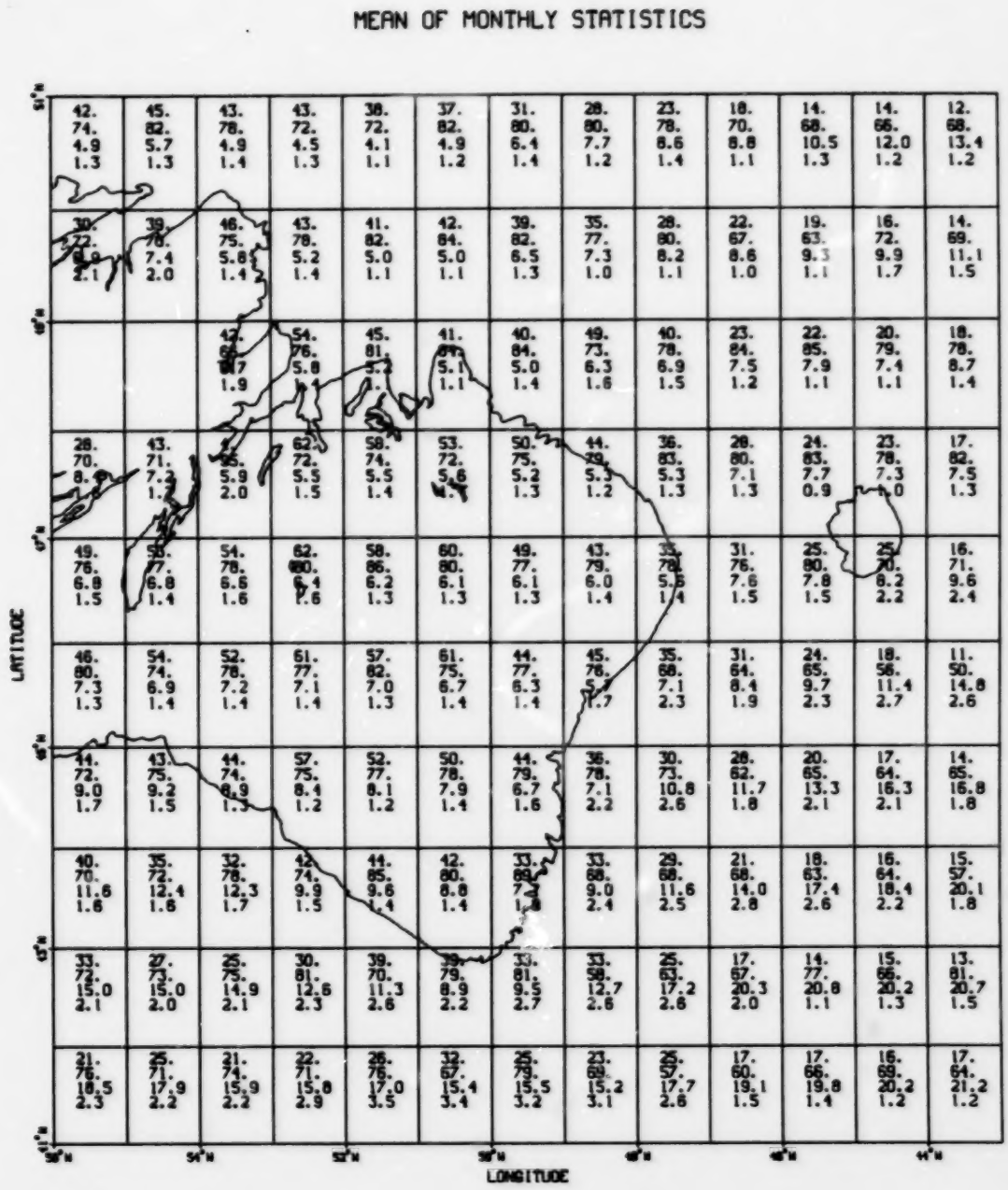

Figure 7: Annual SST statistics. Values represent the mean of the monthly values. The 200m isobath is also shown.

The reduced SST signature of the branch of the Labrador Current in Avalon Channel, is also visible in 7 of the monthly maps. Although the signature is not as strong as that for the mainstream Labrador Current, the flow can be seen as it travels south along Avalon Peninsula, and then veers westwards along southern Newfoundland. Such behavior has been noted by others including Petrie and Anderson (1983), who describe the flow as partially following the coast westward, or moving offshore through the two deep channels south of Newfoundland. The two channels, Haddock and Halibut, make up about 15 and 40% respectively, of the two subareas centered at 45.5° N, 54.5° W and 45.5° N, 55.5° W respectively. Thus, the mean SST signal is not expected to clearly indicate an offshore flow of this branch.

The low temperature surface water which makes up the inshore branch is clearly visible in some individual images. One image, from August 26, 1984 (refer to photographic catalogue in OERD library, BIO) shows the inshore branch as a low temperature region which extends south along the Peninsula and then diverts westwards as it rounds Cape Race.

The high mean temperatures in the south, southeast and northeast sections of the study area are also of interest. To the south, the northern edge of the Gulf Stream with mean water temperatures of O(15-20° C) can be seen. The Stream is also visible in the southeast corner of the study area as it is diverted towards the northeast. Also visible is the North Atlantic Current in the northeastern corner of the study area. The North Atlantic Current is also characterized by warm, O (10° C), water. These positions correspond to previous estimates by Dietrich *et al.* (1980) and Horne and Petrie (1988).

Although the mean temperature field has yielded information on the SST structure on and around the Grand Bank, exchange information may be obtained from an analysis of the variance of temperature in the 1° × 1° subareas. Plots of the standard deviation contours obtained from the monthly statistics are also given in Appendix 2.

The most notable feature in the standard deviation contour plots is the strong tendency for increased variance in the southern section of the study area. In some months the standard deviation in the southern region can be as large as 4° C, while typical values in the northern region are 1.5° C. The contours indicate the presence of the strong temperature front which marks the edge of the Gulf Stream as it flows along the southern region of the study area, eventually being diverted towards the northeast near the Tail of the Bank. The extent to which the contours extend northward indicate the potential importance of the Gulf Stream in the area south of Flemish Cap. This northerly influence of the Stream can also be noted in the eddy kinetic energy (EKE) diagram from Petrie and Isenor (1985), reproduced in figure 8. The diagram shows the area near 45° N 46° W as being a region of high EKE. Together, the diagrams indicate the influence of the Gulf Stream from both its SST and velocity characteristics. The North Atlantic Current loop, previously indicated as being in the northeast corner of the study area, appears as high values in the standard deviation plots for January only.

This study was originally intended to examine exchange between the Labrador Current and shelf water using the standard deviation field. However, inspection of the monthly standard deviation plots indicates no prominant signal of increased variance along the Bank edge. This is probably due to the large scale and local gradients masking the signal of the eddy field. This problem could possibly be corrected by reducing the size of the cells used for the statistical calculation. Alternately, one may inspect individual images to identify eddies in the area of the shelf break and thus identify areas of enhanced exchange from the eddy positions.

WHERE IS THE LABRADOR CURRENT?

The next stage of this work deals with defining the position of the Labrador Current based solely on the available satellite imagery. In this section, SST Current will be the term used to describe the Current boundaries as determined from the IR imagery.

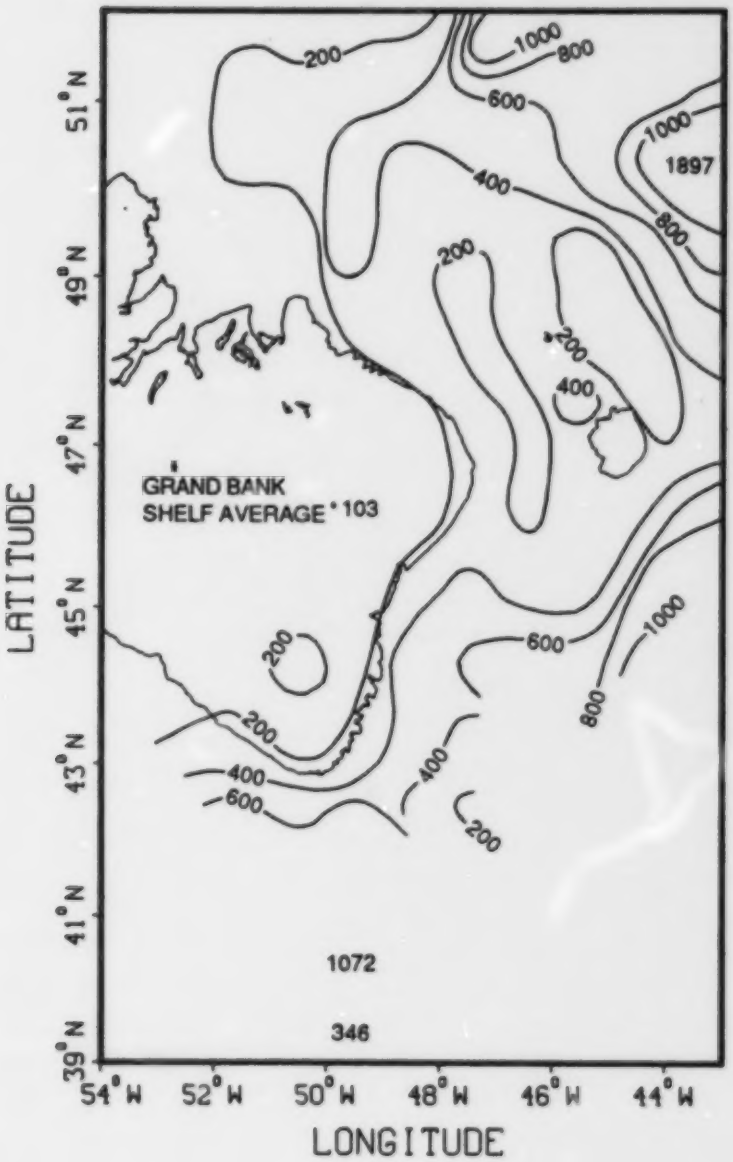

Figure 8: Contours of eddy kinetic energy in units of $10^{-4}m^2s^{-2}$. The $200m$ isobath is also shown. From Petrie and Isenor (1985).

Several recent papers have examined features or dynamics which first required the determination of a current's position from satellite IR imagery. In some cases the actual position of the front was not required, and the position of the core of the feature under investigation could be used (e.g. Ikeda and Emery, 1984). In other cases interest lay in the actual frontal position as determined subjectively using photographs (Mulhearn, 1987) or using digitized imagery (Griffiths and Pearce, 1985).

Although the use of gradients seems the obvious choice when determining a temperature front using a digitized satellite image, some researchers continue to rely on subjective determination. Cornillon *et al.* (1987) subjectively digitized the position of the Gulf Streams northern edge using 8 years of TIROS - N data. Their digitization was based on the findings of Cornillon and Watts (1987) who noted that subjective digitization was found to be more accurate than any of the conventional objective algorithms used. However, subjective determinations of the SST Labrador Current using different look-up tables resulted in frontal positions varying by $20 - 40km$. This is unacceptable considering the Current width is only $\sim 50km$.

Various gradient and variance operators are available in the MIAMI software system. These operators were investigated for this study and found to be inappropriate for use in boundary determination. The primary problem appeared to be the small scale variance (on the order of pixels) in the temperature field which resulted in much noise even after applying a reasonably large filter (7×7 pixels). Thus, the small scale variability, thought to be at least partially due to the discontinuous nature of the temperature field, almost totally obscured the gradient and variance signal of the SST front.

The inability of the available routines to detect the SST Current boundaries instigated the development of software whose sole purpose was to objectively determine the boundaries of the SST Current. Noting that the Labrador Current typically follows the edge of the continental shelf, approximately parallel the $200m$

isobath, one could consider an algorithm which determines the gradients in the x direction (east–west) only by dividing the image into many boxes and calculating the gradient in box i from the means in boxes $i+1$ and $i-1$. For this study the box size will be 3×5 pixels or $6km \times 10km$ ($2km$ resolution imagery will be used) in the x and y (north–south) directions respectively. The slightly larger y dimension is to take advantage of the increased uniformity of the temperature field in the y direction while the x dimension is reduced so as to increase the boundary resolution in the cross current direction.

The primary assumption used in the algorithm is that the Current's SST boundary can be determined using the gradient in the mean temperature field along x. The second assumption used is that the minimum SSTs will be found within the boundaries of the SST Current. This assumption uses the fact that the Labrador Current is a cold current bounded to the west by the warm shelf water and to the east by the warm North Atlantic Current. This restricts the program in that cloud features must be avoided.

Given these two assumptions, the algorithm proceeds as follows. In the first step the minimum, maximum, mean, gradient and standard deviation of temperature for each box in a particular row are determined. The 5 largest negative (western boundary) and positive (eastern boundary) gradients are noted (10 in all). Then, applying assumption 2, the algorithm searches each row for the boxes which contain the minima in the mean, minimum and maximum temperature. The most stable statistic is considered to be the mean, thus the lowest mean temperature is considered to have a higher probability of being within the SST Current. Consequently the standard deviation of temperature from the box with the lowest mean is considered to represent the variance of the temperature field within the SST Current. The standard deviation from the box with the lowest mean is then added to the minima to obtain upper limits on the 3 statistics. The algorithm then searches eastwards and westwards of the minimum value boxes (at least 3 boxes) until finding values which exceed the minima plus one standard deviation. Thus, one obtains at least 6

first order estimates of the SST Current edge, 3 for the western edge and 3 for the eastern. These estimates are further refined by searching outward (e.g. towards the west (east) for the western (eastern) boundary) for the nearest of the 10 large local gradients. The box which contains the large local gradient is the determined boundary. Finally, the 3 estimates of the boundary position, now based on the gradient, are compared and the box which has most often been declared as the boundary is defined as the actual boundary.

Two oddities exist within the algorithm. The first deals with the addition of the standard deviation to the minimum values. This procedure was incorporated into the algorithm in an attempt to reduce the erratic boundary positions output from the program where the SST Current feature widens north of 47° N. In this area, the Labrador Current is travelling towards the south-east, and thus the gradient in the x direction is not as strong as when the Current flows toward the south. The increased SST Current width also seems to produce increased small scale temperature variance within the SST Current (a subjective observation). This also contributes to erratic boundary positions. The addition of the standard deviation gave improved results for the region north of 47° N. For the test images considered, the addition of the standard deviation did not greatly effect the region south of 47° N, because the Current in this region is much narrower and homogeneous.

The second oddity deals with the search procedure for the large local gradient. Obviously, the term "large" must be quantified for such a routine to execute, but the actual magnitude of the gradient is in question. To avoid applying a magnitude limit to define "large", the entire row of boxes is examined and the 5 largest negative (western boundary) and positive (eastern boundary) gradients are noted (10 in all). To avoid the possibility of one feature dominating the group of 5, only non-consectutive gradients can appear in the group. When the routine searches outward from the estimated boundary for a large local gradient, it can only choose one of these 5 local gradients. It should be noted that the largest gradient in the row is not necessarily a good indicator of the boundary.

To investigate the varying effects of the application of the 3×3, 5×5, and 7×7 median filters, consider the frontal boundary positions from the image of October 31, 1984. The boundary positions using the raw image and the raw image after the application of each filter (4 images in all) were determined and then compared for the area south of 47° N. Several worthwhile points can be made. First the large deviations, $O(10km)$, observed between the raw and the filtered 3×3 image boundaries are expected as the boundary program (hereafter BP) makes use of the minimum, maximum and standard deviation of temperature in the $6km \times 10km$ box. Secondly, the mean difference between the 3,5 and 3,7 (where the numeric refers to the filter applied) comparisons were found to be relatively low at $< 5km$ while the standard deviation of the differences was steady at $13km$ ($9km$) for the western (eastern) boundary. The stability of the values for the 2 comparisons is thought to indicate stability in the frontal boundary positions from the 5×5 and 7×7 filtered images.

To eliminate as much small scale variability as possible while still maintaining a reasonable boundary resolution, all images have been filtered with a 5×5 median filter. Such a filter will reduce the small scale variability while maintaining linear features on scales equal to or greater than 3×5 pixels, the box size used in the BP. Thus, such filtering will not effect linear features on scales of the box size in the BP.

From the data base of 98 images, only 23 were used to determine the boundaries of the SST Current. The reduction in the amount of imagery was due to cloud cover (53 images omitted) and because of no low temperature region or SST Current signature (22 images omitted). To eliminate the obvious problem of consecutive day images, high temperature composites were produced. This resulted in the final data base consisting of 15 independent images, with 5 of these 15 representing composites of 2 or more images (table 4).

A final consideration should deal with the determined boundary position. Obviously, parcels of water at the boundary do not merely move in an east - west

Table 4: Dates of images used to calculate the mean SST Current position. A "*" denotes a composite.

YEAR		DATE
1984		May 4
		June 6
	*	June 26 & 27
		August 16
		October 5
		October 31
1985		July 18
	*	October 4,5 & 6
	*	November 4 & 5
1986		January 13
		March 19
		April 14
	*	May 14,15,16 & 17
	*	October 8 & 9

direction at a unique latitude. However, the digitization of the front may imply this at a later stage when plots of the standard deviation in the boundary are shown.

As a first attempt to determine the reliability of the BP, the mean position of the Current was produced (figure 9). Means were calculated by taking the algebraic sum of all frontal positions in zones of 0.1° latitude and then dividing by the number of positions. This method has obvious problems as a general set of arbitrary two dimensional curves do not possess a unique mean. Thus, means calculated in different coordinate systems will yield different answers. Methods have been presented for dealing with this problem (Olson *et al.*, 1983) although such in depth analysis may not be warranted for so few images as in this case.

Using 15 images implies the maximum number of independent estimates is 15. However, cloud usually obscures part of the image thus dropping the maximum number of estimates to 13. The central portion of the Bank from 43.5 to 46.5°N all have 10 or more estimates. The large variability of the frontal positions above 48.5° N is not only a result of the low number of estimates, but is also an artifact of the extreme temperature variability of the Current in this area, and the detrimental effect this variability has on the BP. The smooth nature of the mean SST Current position is obviously not sufficient to determine the reliabliity of the BP, however, it is encouraging.

ANOMALOUS EVENT

The boundary positions, as determined from the November 1985 imagery, are shown in figure 10. Comparing this with the mean one notes the most pronounced differences near Southeast Shoal and the Tail of the Bank. In an attempt to quantify the widening/shift, consider the width of the mean Current and the width of the November 1985 composite shown in figure 11. Although the large spikes in the November width make comparison difficult, there appears to be a slight widening of the November Current relative to the mean. Indeed, comparisons of the average

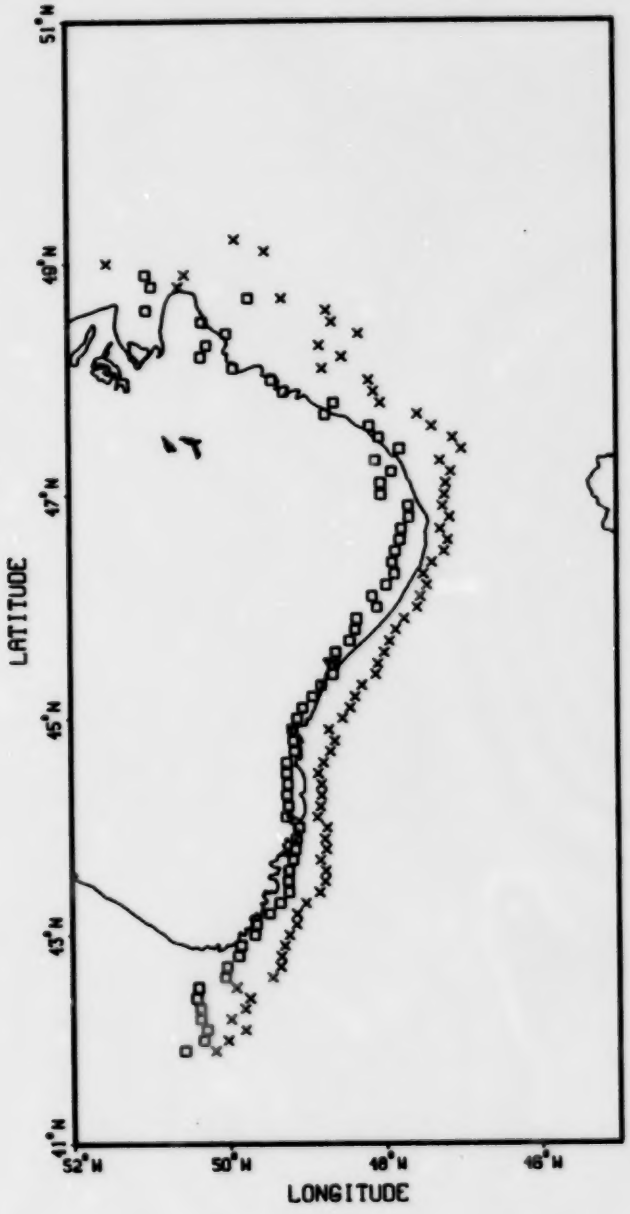

Figure 9: Mean SST Current position. "□" denotes the western boundary and "×" denotes the eastern boundary. Solid line denotes the 200m isobath.

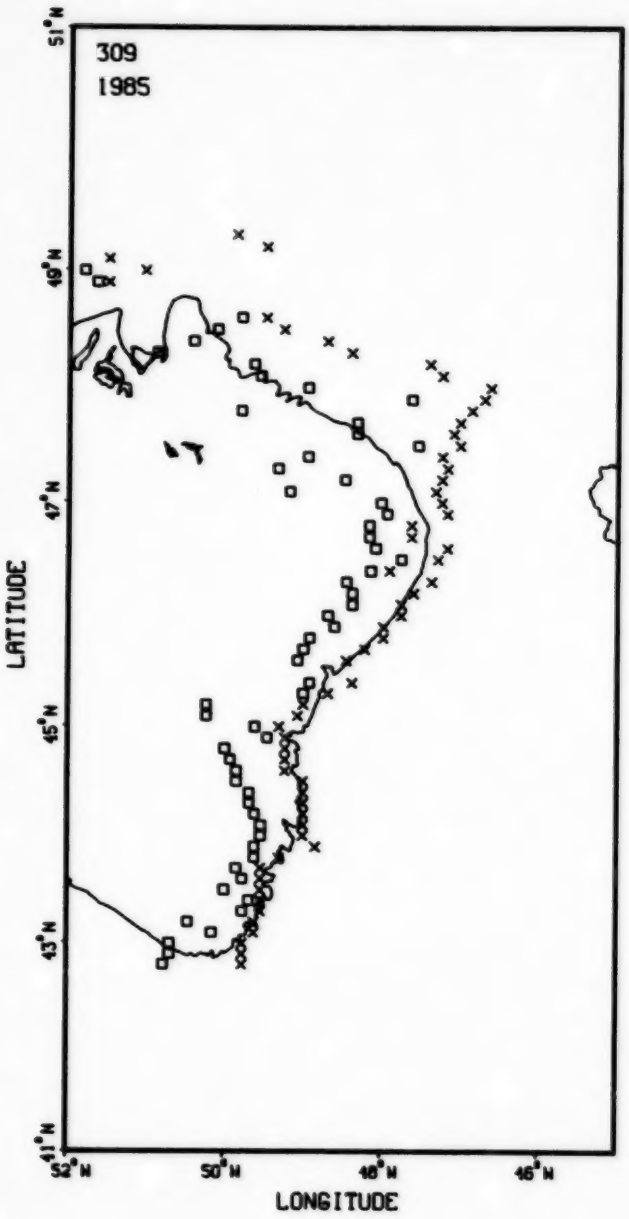

Figure 10: Boundaries of the November 1985 SST Current as defined by the boundary program. "□" denotes the western boundary and "×" denotes the eastern boundary. The 200m isobath is also shown.

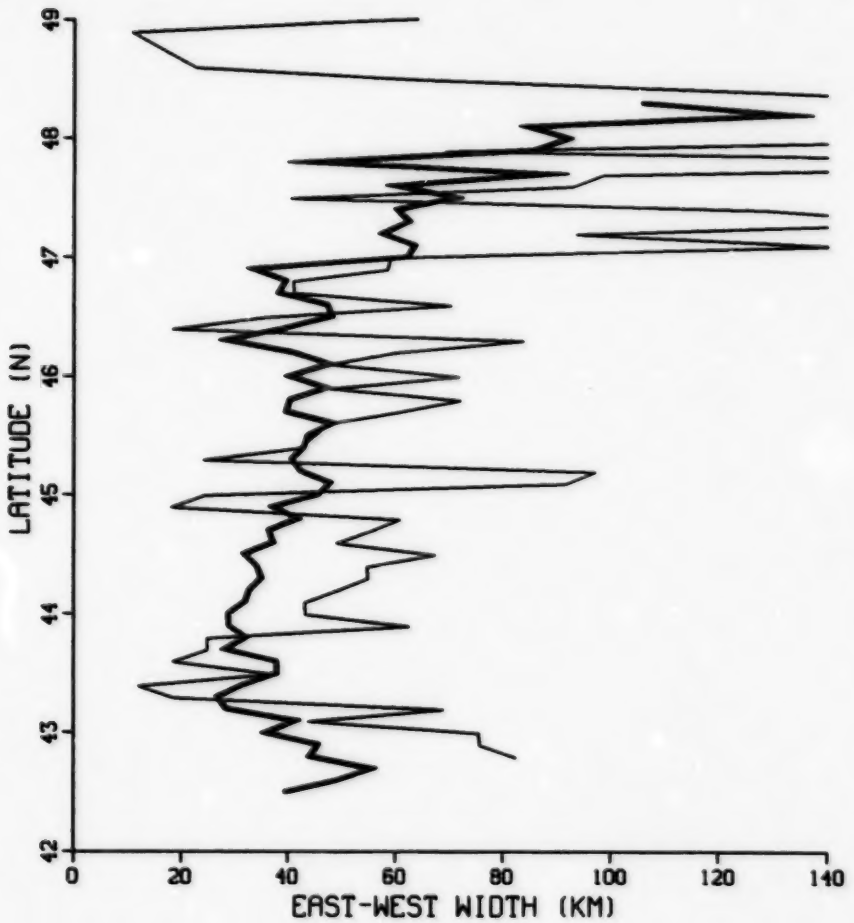

Figure 11: Comparison of the width of the November SST Current (thin line) and the mean SST Current (thick line). Here, width refers to the east-west distance between the two boundaries.

current widths (table 5) indicates that the November Current is $12 \pm 3km$ wider than the mean between 43° N and 46.9° N.

To consider the shift of the SST Current, first note that if the magnitude of the shift is greater than the widening, then some lateral movement of the Current has taken place. Indeed this is the case during November 1985 as can easily be seen in figures 12 and 13 where the difference in the western and eastern boundaries are given. These figures show the magnitude of the boundary shift in the November 1985 imagery relative to the mean SST current position. Also shown are regression lines (see table 6).

Several factors are worth noting when examining figures 12 and 13. First, the overall shift in the SST Current ($\sim 30 - 60km$) is much greater than the apparent shift resulting from widening ($12km$). Thus, the primary alteration of the SST Currents position is the lateral shift, with only a small amount of widening. Secondly, the magnitude of the shift increases in the southerly direction. The correlation coefficients given in table 6 indicate that the increase is significant at the 99% level. The slope of the regression line is also significantly negative.

As a final comparison of the November 1985 SST Current, consider the standard deviation of the boundaries (figures 14 and 15) compared to the November SST Current position (figure 10). Obviously, the November shift near Southeast Shoal is considerably more than 1 standard deviation for both boundaries. This is further exemplified by table 7, where the mean difference in multiples of the standard deviation are given over 1° increments. The shift for the western (eastern) boundary south of 46° N averages 2 SD (1.6 SD).

CONCLUDING REMARKS

There have been several worthwhile results from this analysis. The monthly maps of SST statistics represents a 3 year data base of NOAA imagery for the Grand Banks. These statistics have been shown to be indicative of the water temperature

Table 5: Comparison of the average current widths from the mean and the November images. Here, width refers to the east--west distance between the two boundaries.

Latitude Increment	Nov. (km)	Mean (km)	Difference (km)
47.0 - 47.9	111	66	+45
46.0 - 46.9	53	40	+13
45.0 - 45.9	56	44	+12
44.0 - 44.9	50	35	+15
43.0 - 43.9	39	33	+ 6

Table 6: Regression lines shown in figures 12 and 13. Lines are based on least squares fit to $bx + a = y$ where x is latitude, and y is shift in km. The regression lines are calculated using all boundary points south of 47° N. Also given is the correlation coefficient r and the 99% limits on r, denoted ρ.

Units of a and b are km and (km/degree) resp.

	Western	Eastern
a	429.9	368.0
b	-8.6 ± 2.6	-7.5 ± 2.2
r	-0.46	-0.47
ρ	-0.1,-0.7	-0.1,-0.7

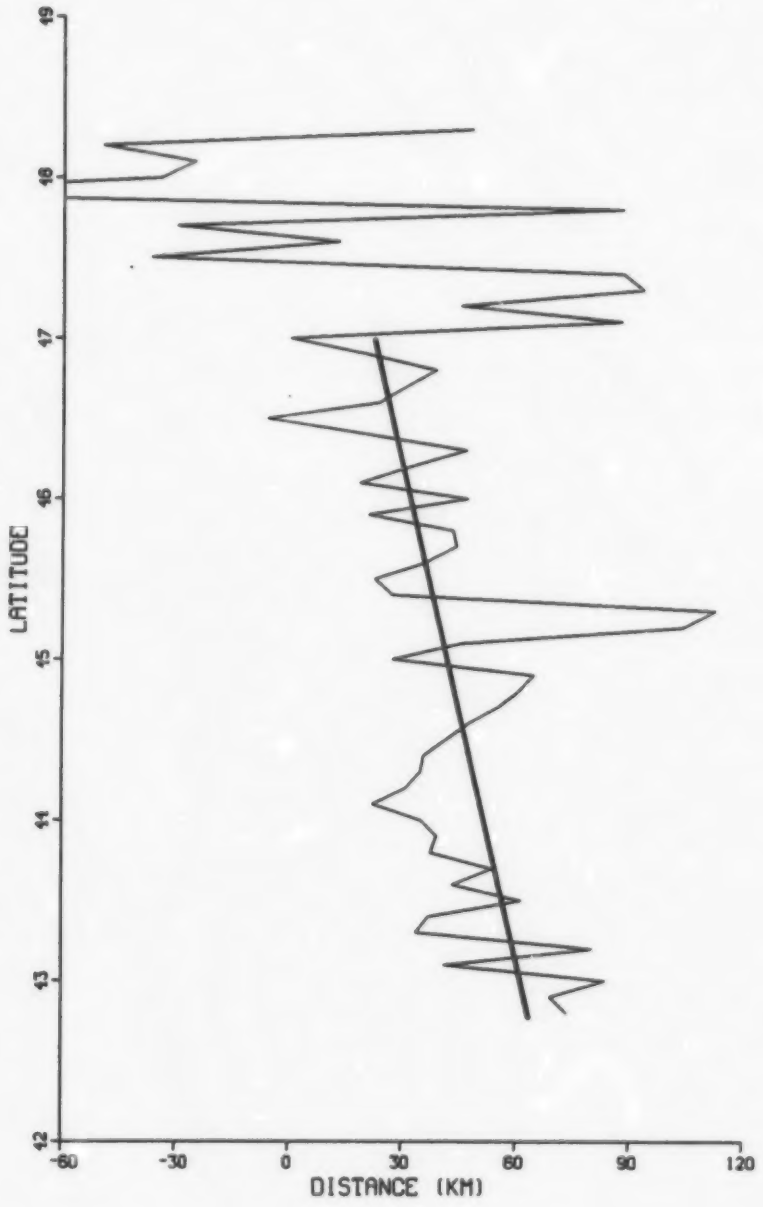

Figure 12: The difference between the November and the mean SST Currents western boundary. Also shown is the regression line (see table 6).

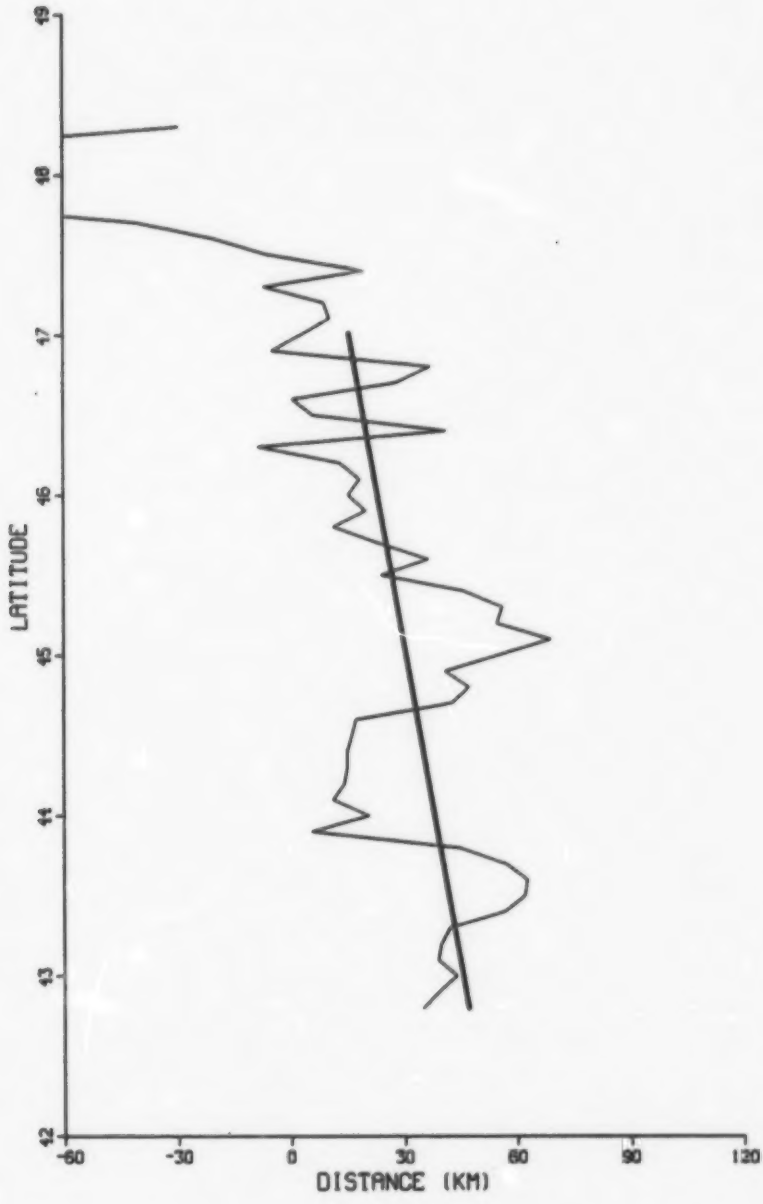

Figure 13: The difference between the November and the mean SST Currents eastern boundary. Also shown is the regression line (see table 6).

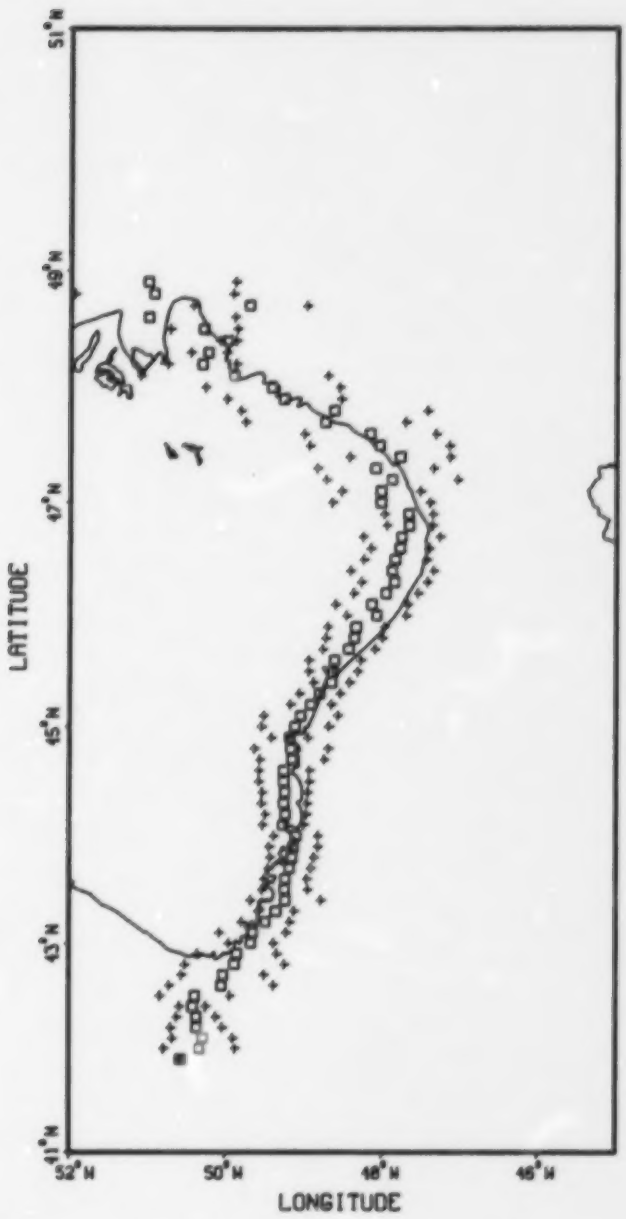

Figure 14: The western boundary of the mean SST Current, denoted by "□", and one standard deviation on either side, denoted by "+". Also shown is the 200m isobath.

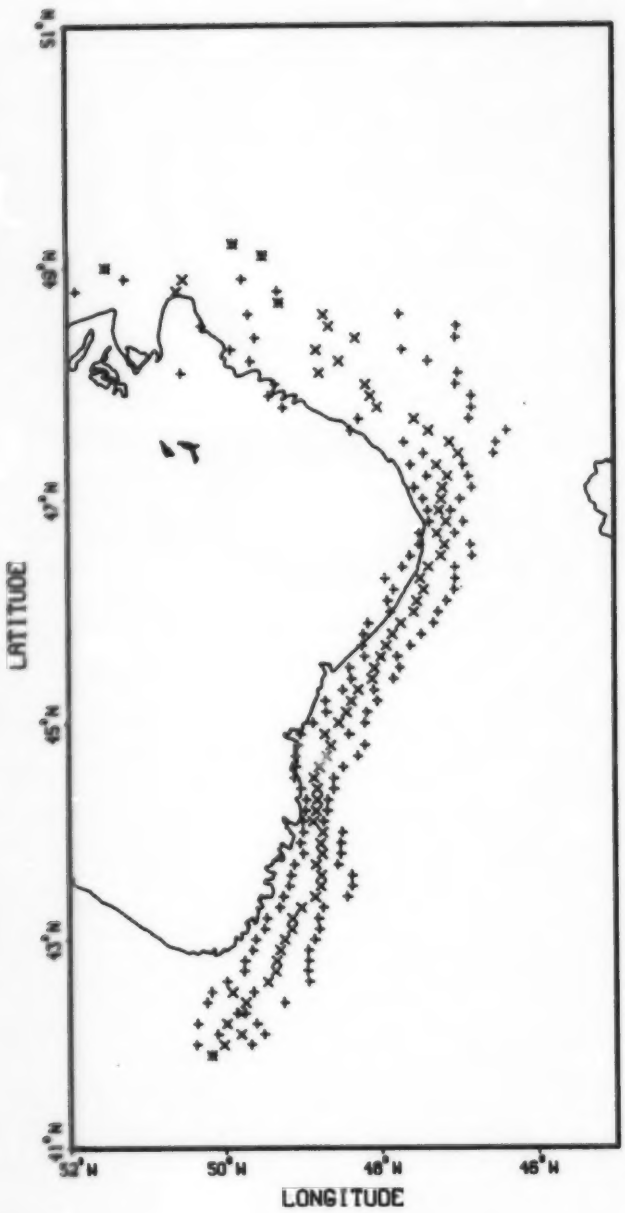

Figure 15: The eastern boundary of the mean SST Current, denoted by "×", and one standard deviation on either side, denoted by "+". Also shown is the 200m isobath.

Table 7: Shift of the boundaries in units of standard deviations over 1° increments, in the north–south direction.

Increment	Shift of western boundary	Shift of eastern boundary
47.0 - 47.9	0.4	-0.2
46.0 - 46.9	0.9	0.7
45.0 - 45.9	2.1	1.9
44.0 - 44.9	1.8	1.2
43.0 - 43.9	2.1	1.7

over the upper layers of the water column and thus may be useful for future studies requiring surface layer temperatures.

The original goal of examining exchange using the variance field has not been achieved. The analysis, using $1° \times 1°$ cells, resulted in no indication of increased variance along the Bank edge. However, reduction of the cell size or the inspection of individual images may still yield exchange information.

Defining the position of the SST Labrador Current was also successful. The algorithm, although not very arbitrary, resulted in two smooth, well defined boundaries for the mean SST Current. Efforts are presently underway to position the mean SST Current relative to the underlying velocity structure.

A preliminary examination of an anomalous event in November 1985 showed that the SST Current had been displaced westward by approximately $50km$, or 2 standard deviations. The results presented here represent the initial stages of a continuing effort to explain this event further.

ACKNOWLEDGEMENTS

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APPENDIX 1

Statement of Work

The contractor will carry out the following work with the set of satellite infrared imagery tapes for the period January 1984 – December 1986.

1. Based on the quick look files already available, the contractor determines which images show significant areas of the Grand Banks which are clear. A brief catalogue should be prepared indicating acceptable images and rating the coverage (e.g. entire Banks clear, northern Banks clear, etc. and/or by cloud power in the image field).
2. Based on the catalogue created above, the contractor will process the image tapes on our image processing system using the Miami software package in consultation with the scientific authority. The contractor will create a catalogue of these processed images for reference. Where appropriate, the contractor should supply brief notes on the image field which identify problems encountered during processing (e.g. anomalous features in the field due to thin cloud.)
3. Based on the set of useful infrared imagery created above, the contractor will determine the distribution of temperature variance in the Grand Banks – Labrador Current region. This will involve computations over areas designated in consultation with the scientific authority. It will focus on the Grand Banks, slope region, Labrador Current, Slope Water and Avalon Channel. The software to carry out these computations is the responsibility of the contractor.
4. Based on a review of the entire (useful) imagery set the contractor will identify areas of enhanced eddy activity and will define the position of the Labrador Current, when it is well marked by a temperature front, relative to the local bathymetry.

APPENDIX 2

Appendix 2 contains the monthly SST statistical maps and the contoured mean SST and standard deviation fields. Each cell in the monthly SST statistical maps contain:

number of images

percentage of points

mean temperature (°C)

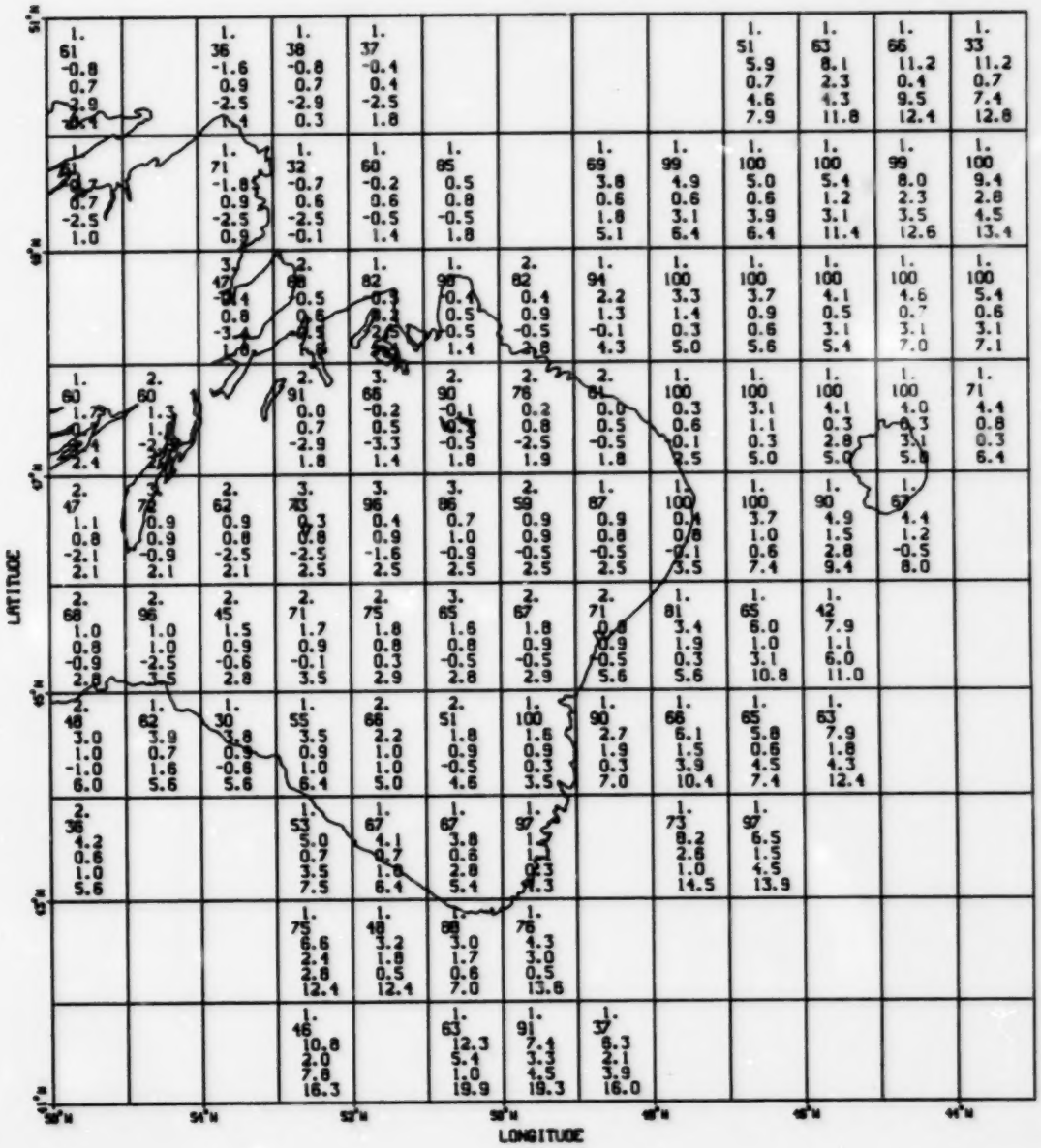
standard deviation in temperature (°C)

minimum temperature (°C)

maximum temperature (°C)

The mean SST field (left side of page) is contoured at 2°C intervals while the standard deviation field (right side of page) is contoured at 1°C intervals. In all figures, the 200m isobath is indicated as a broken line.

JANUARY STATISTICS



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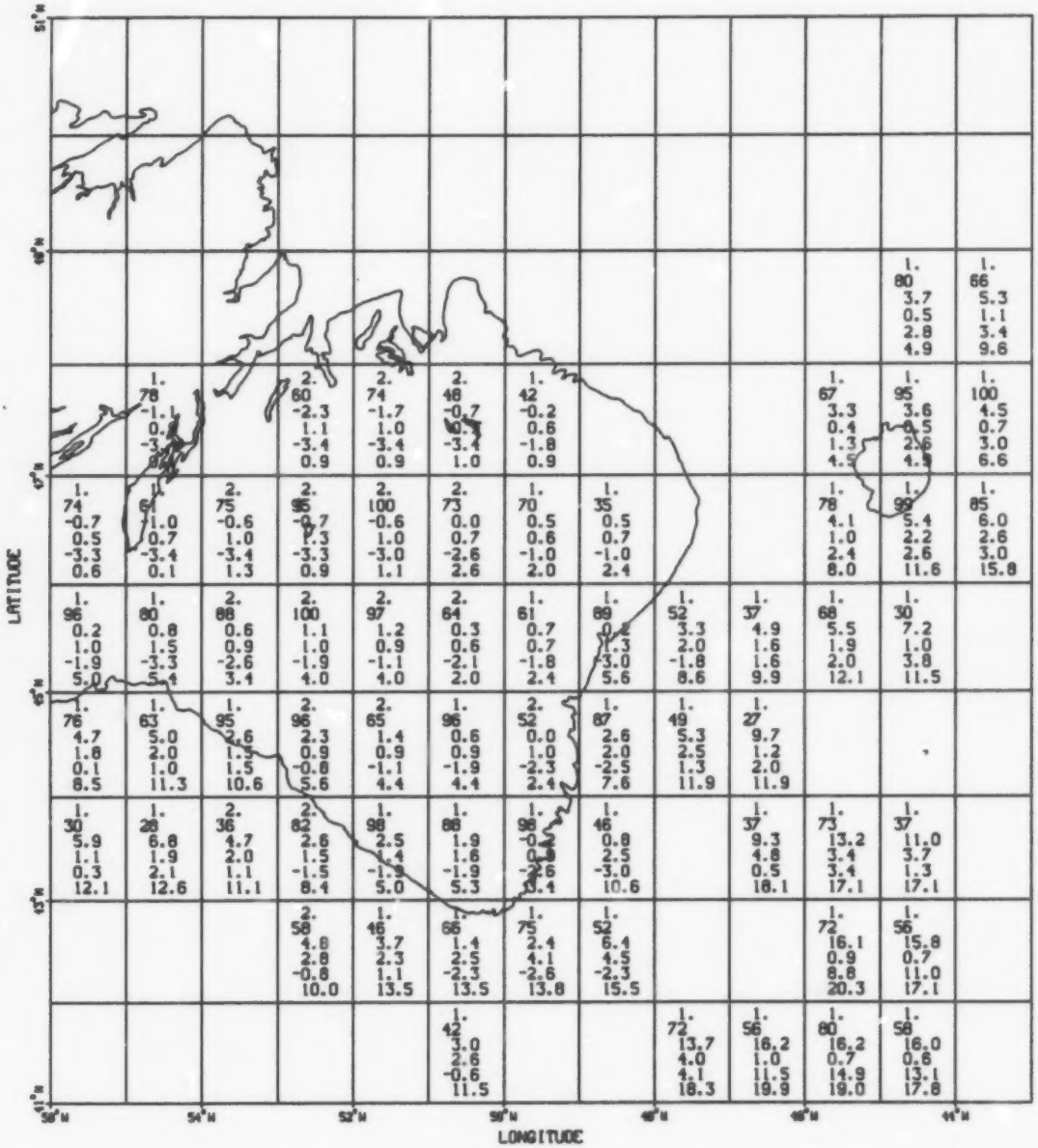
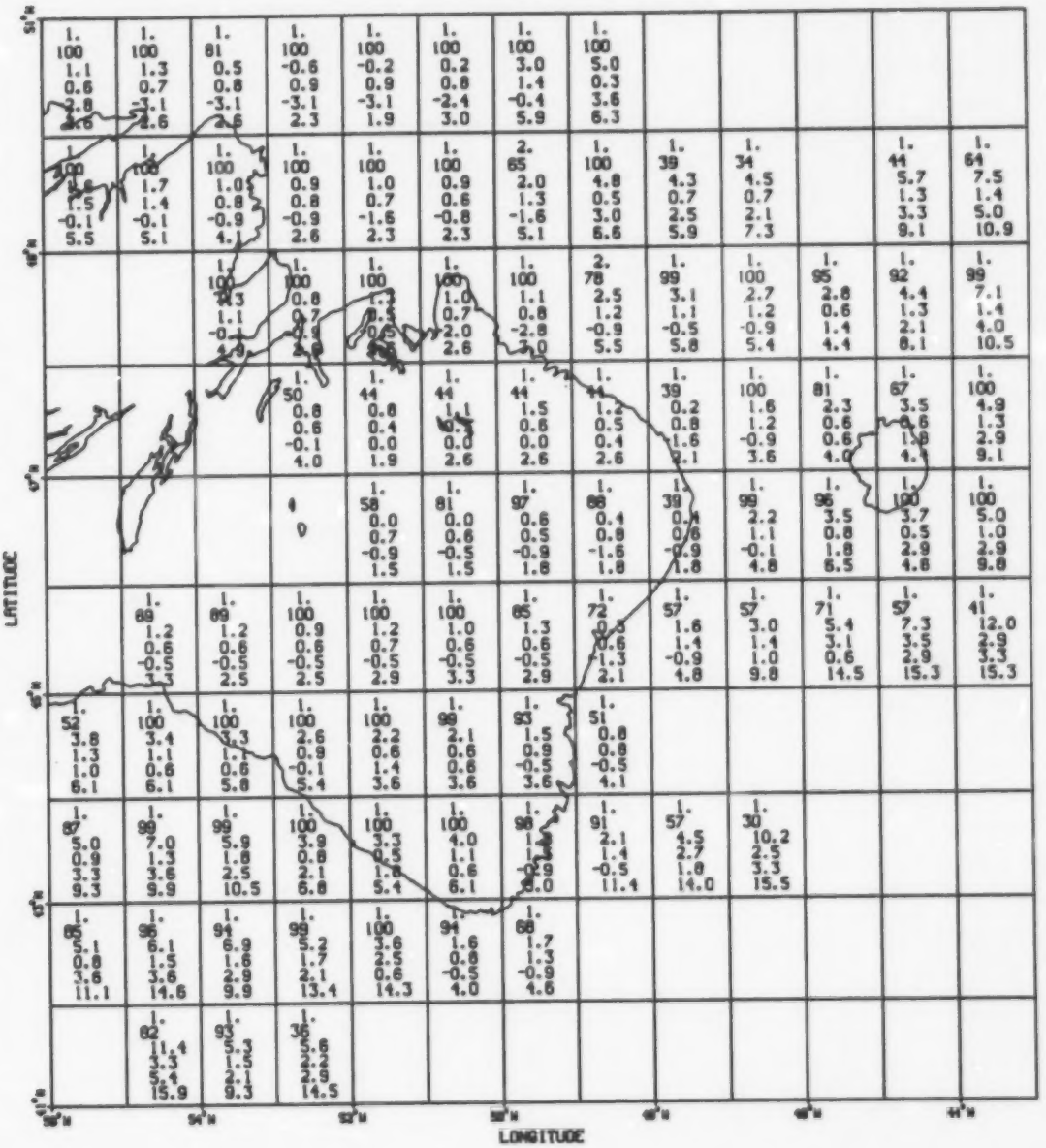


MARCH STATISTICS



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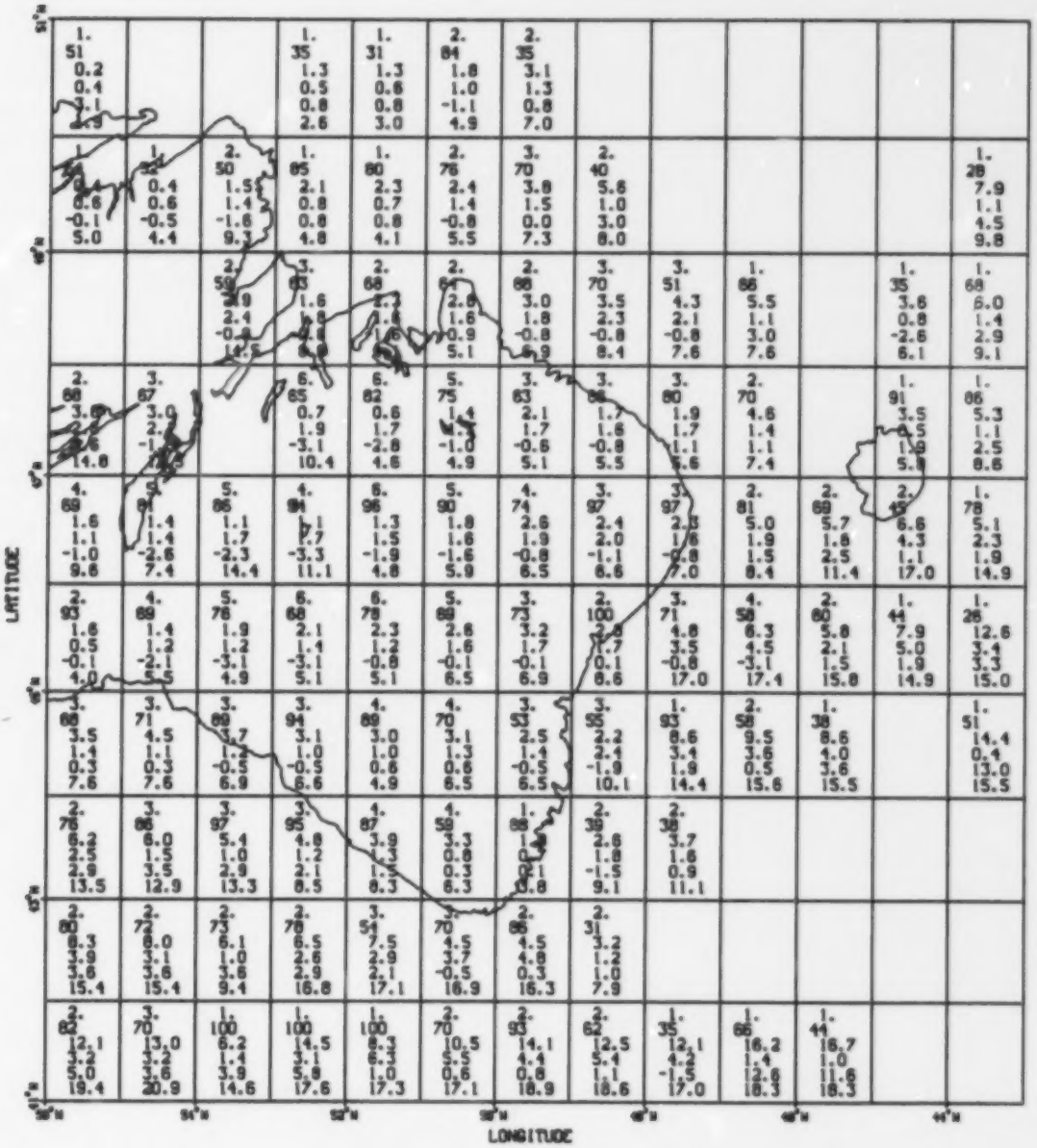

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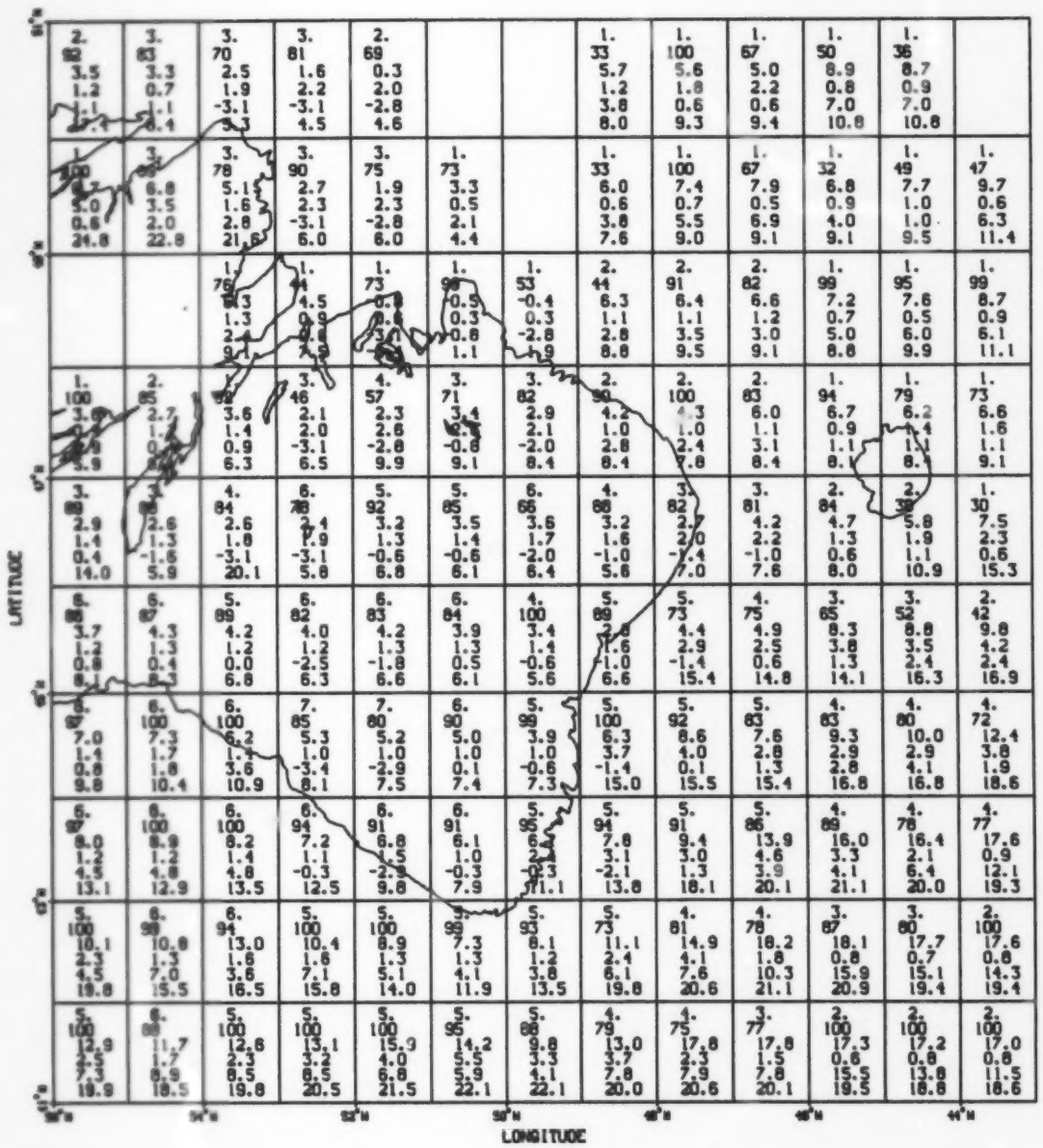

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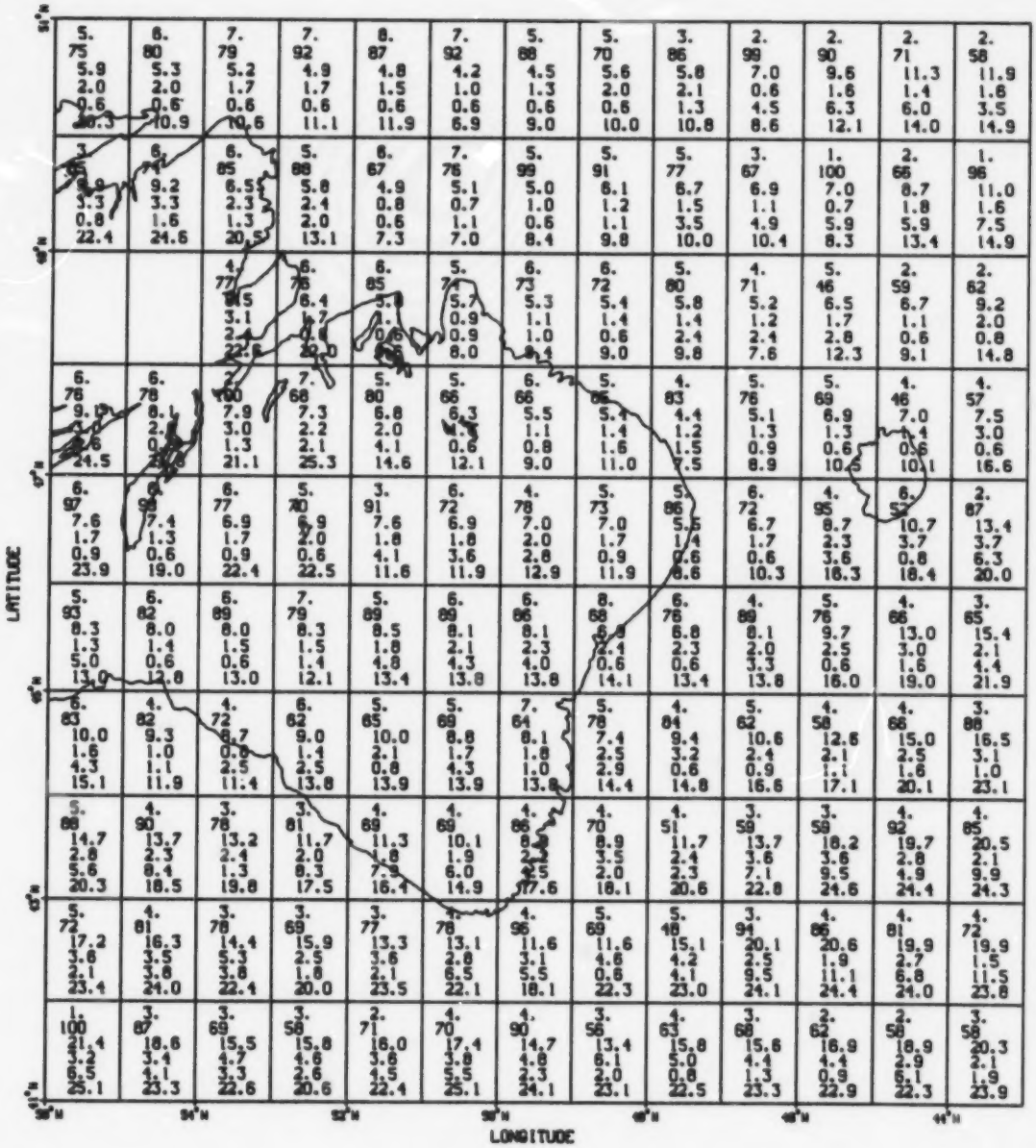

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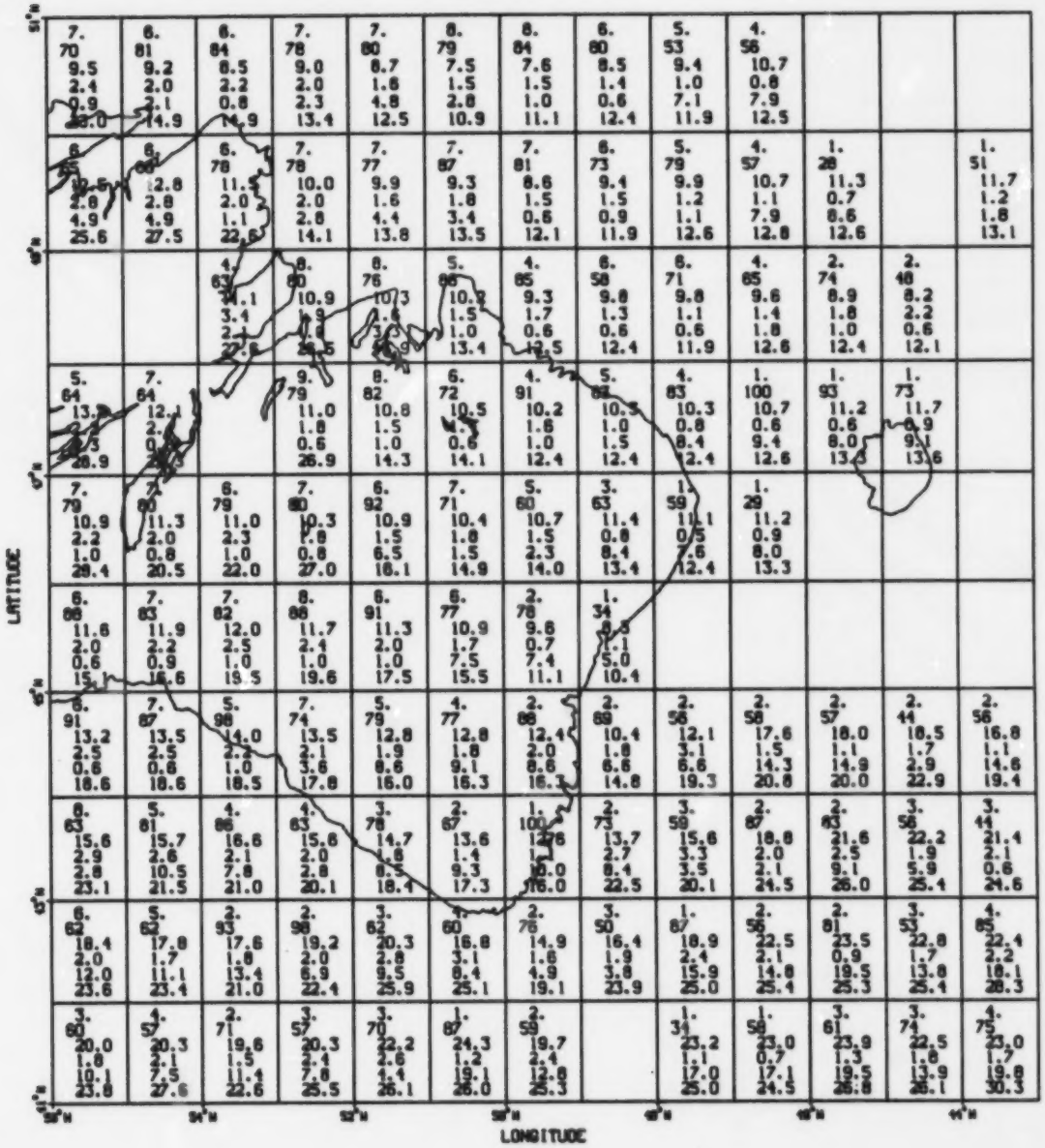

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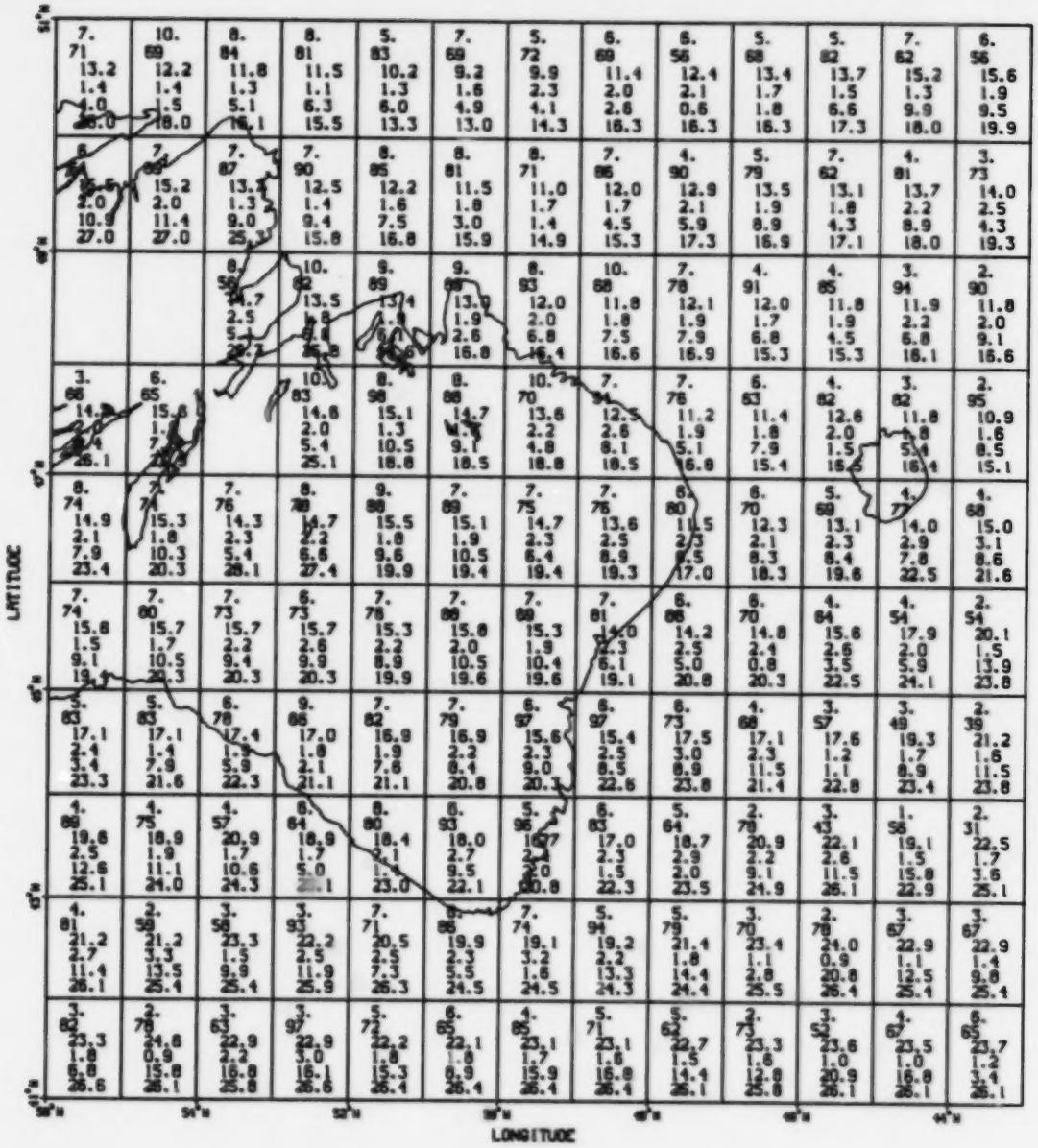

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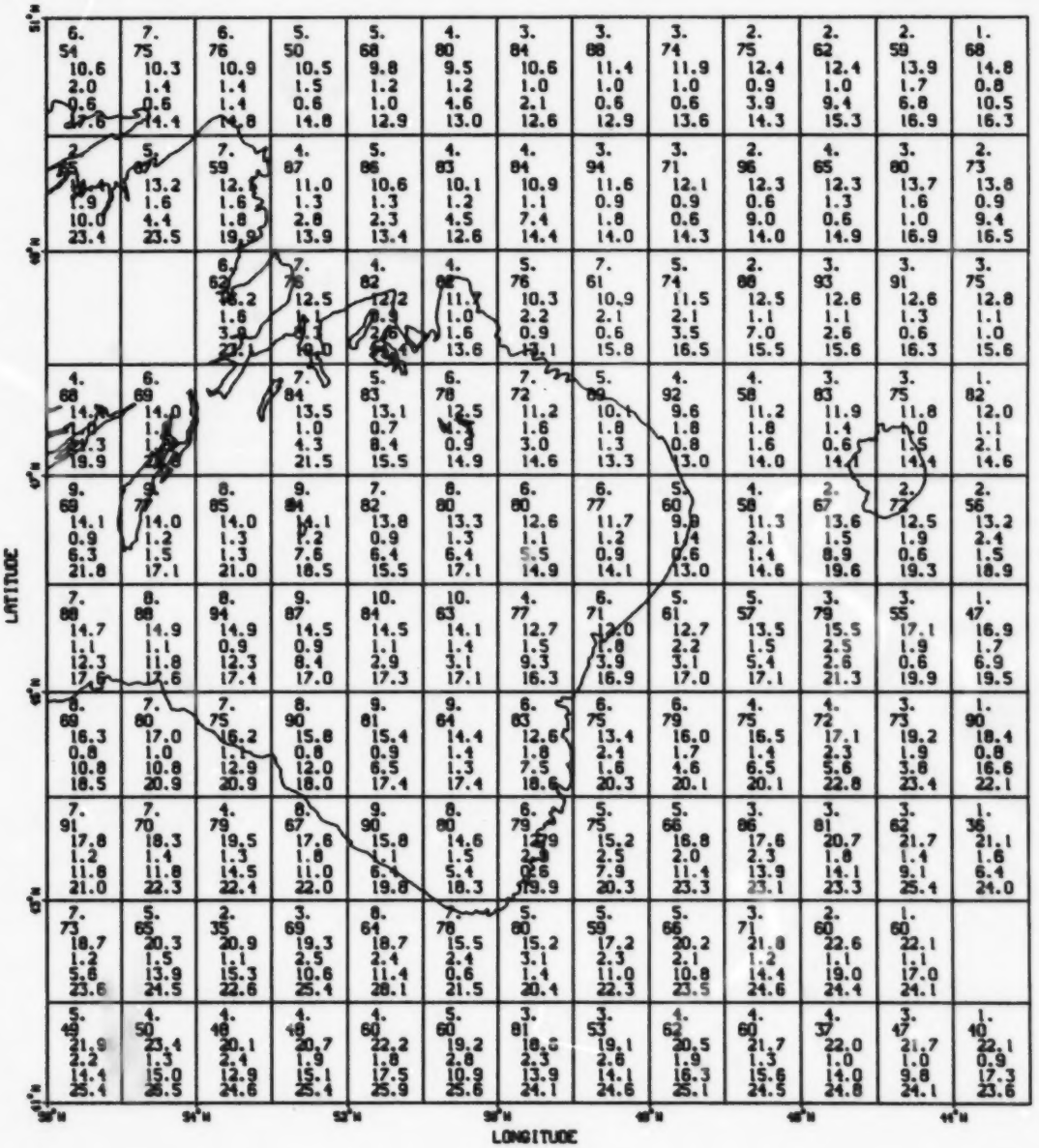

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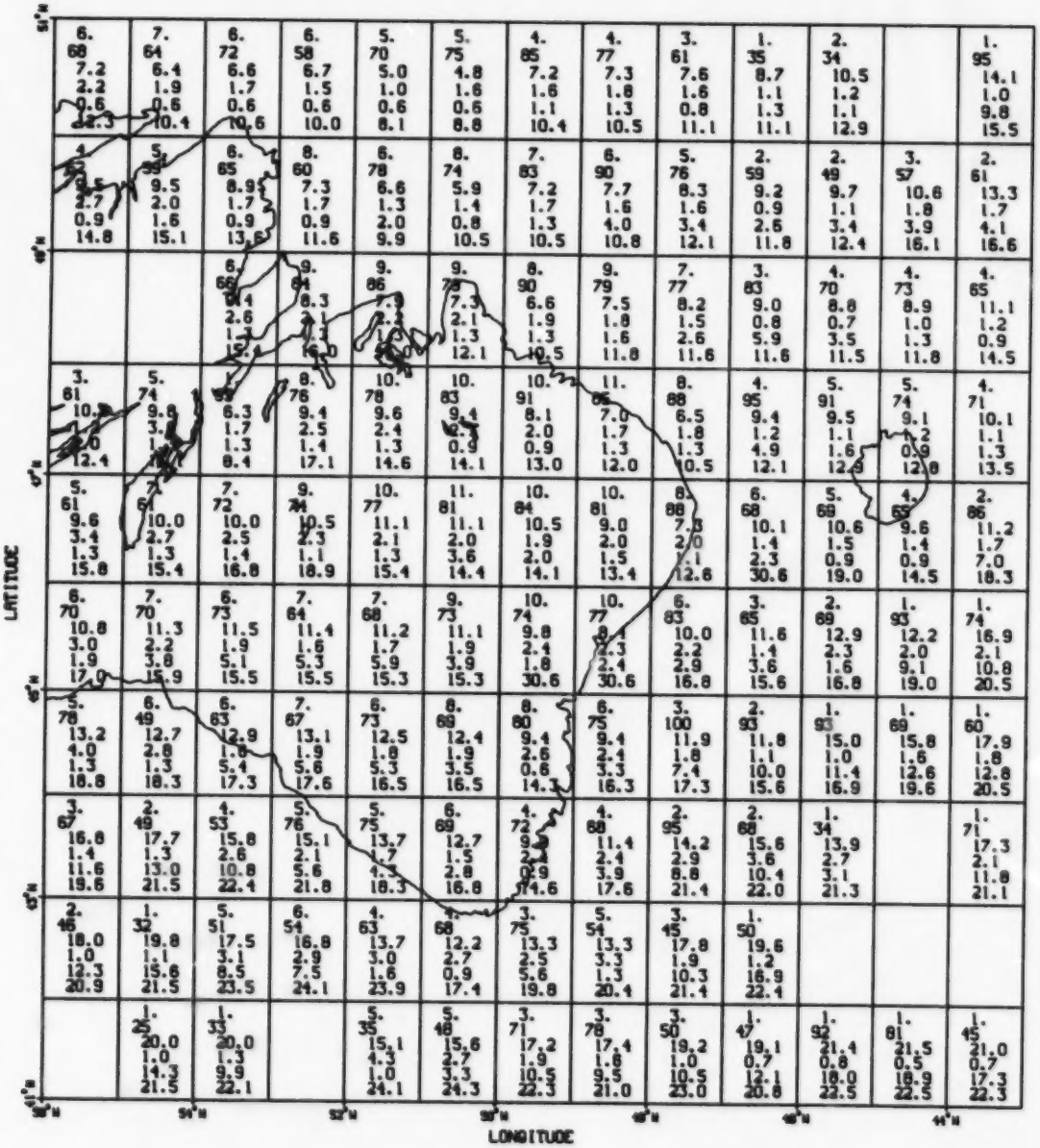

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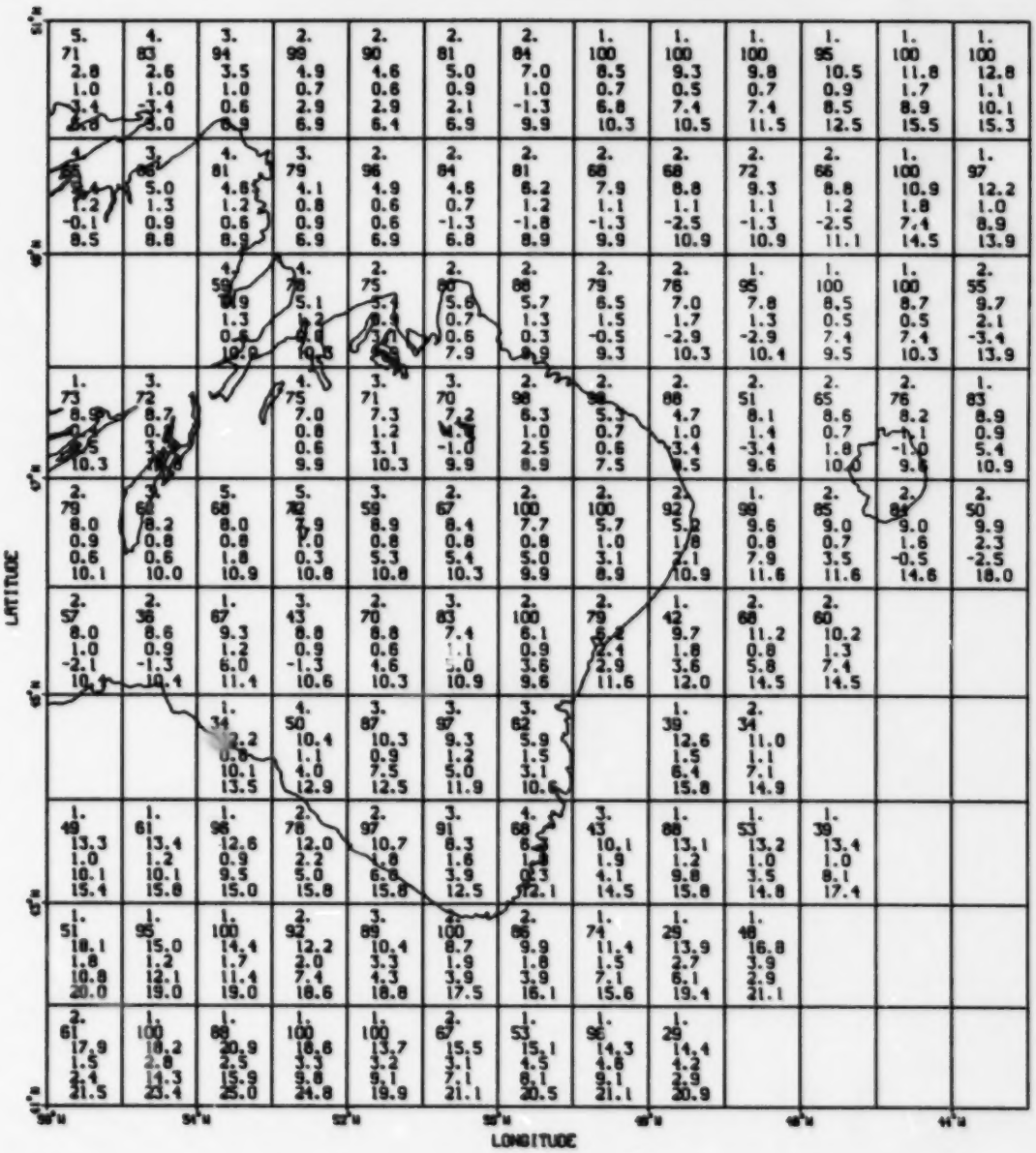

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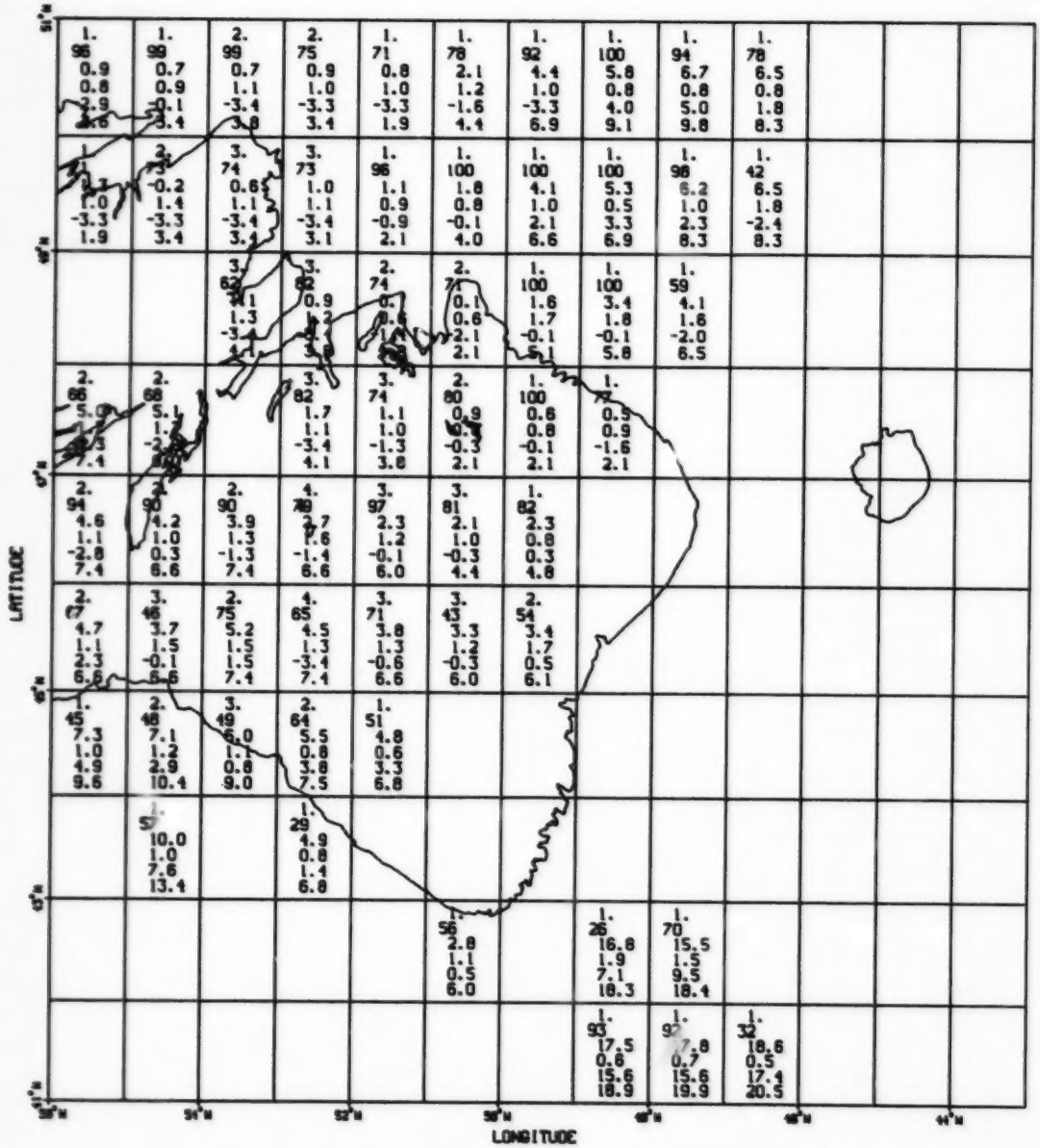

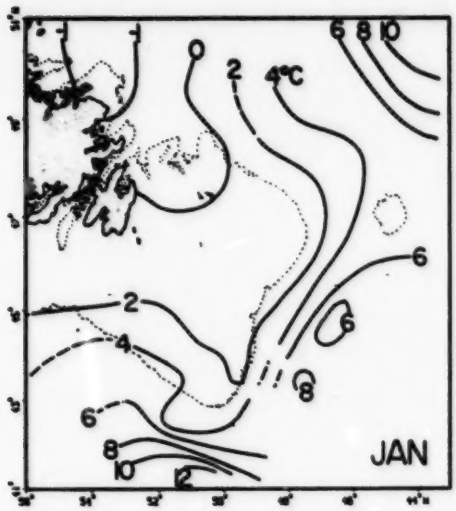
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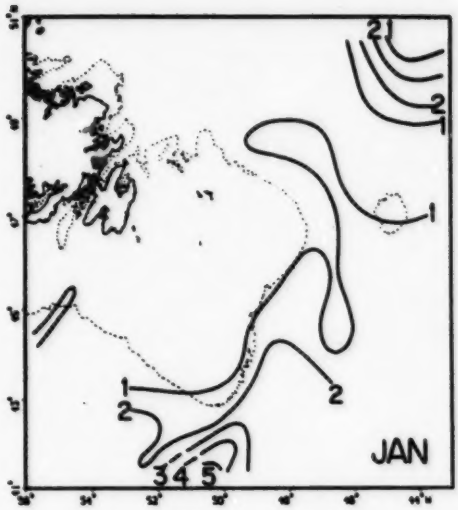
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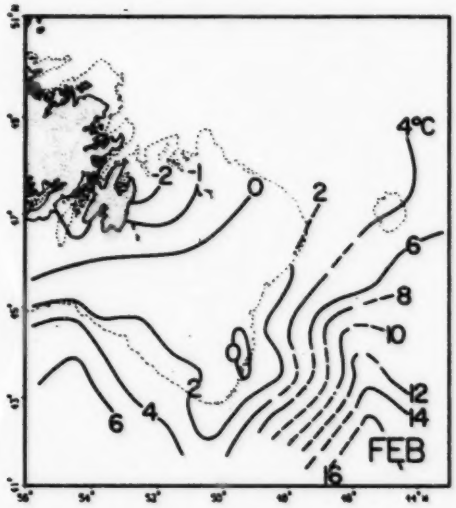
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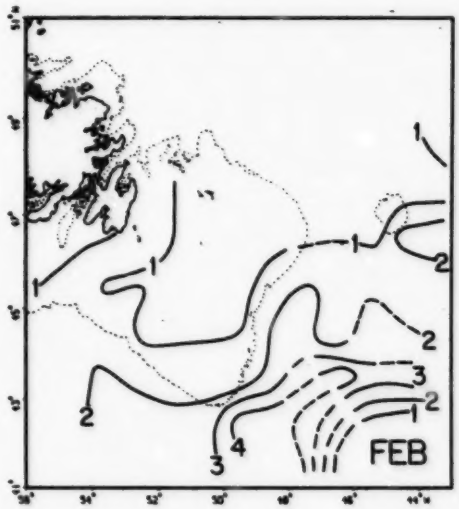
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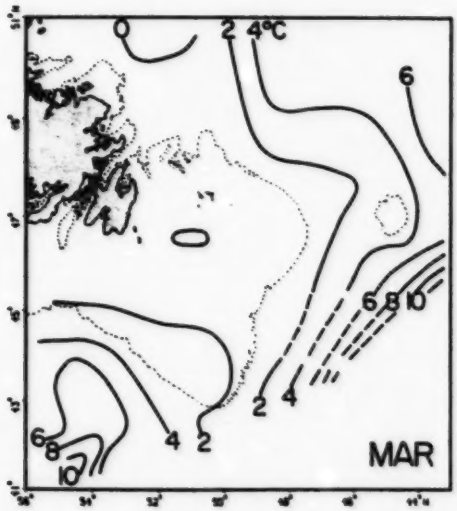
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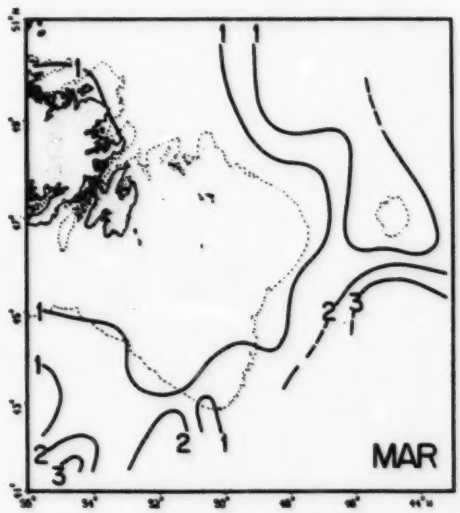
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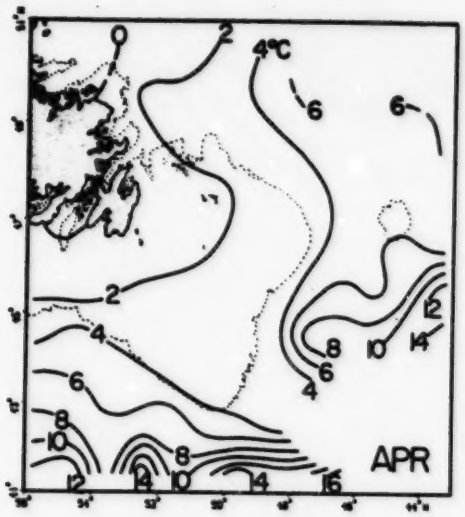
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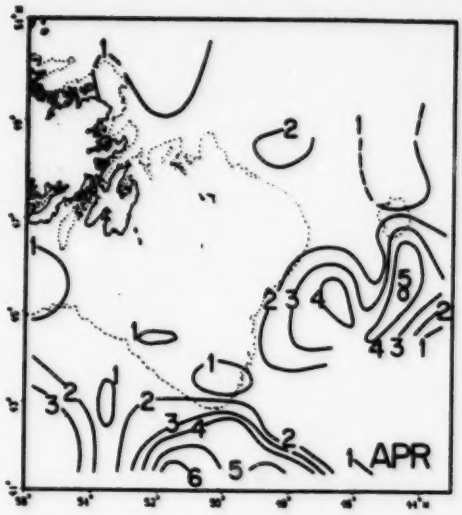
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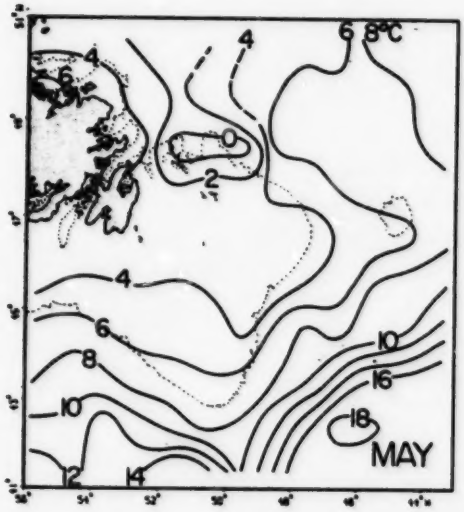
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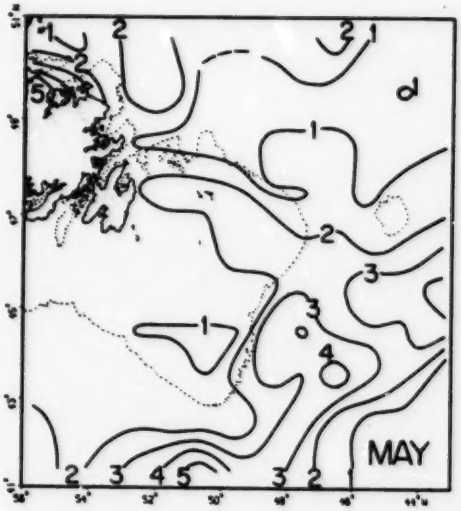
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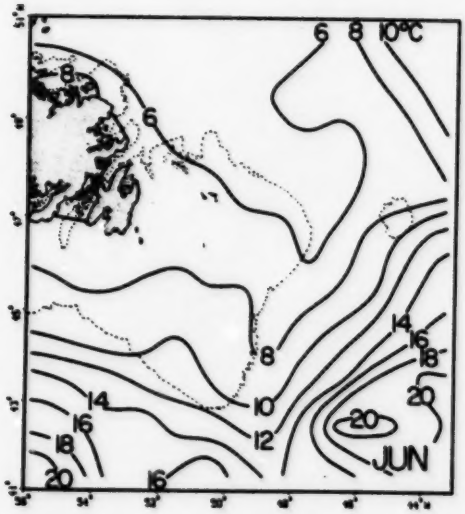
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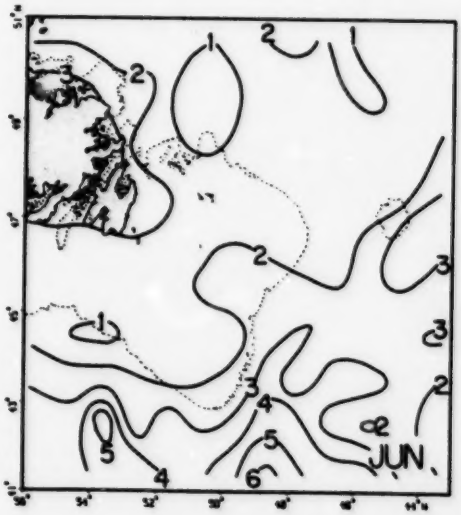
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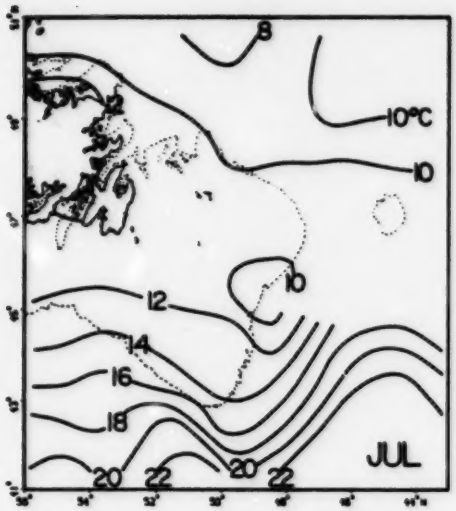
8
10°C
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JUL

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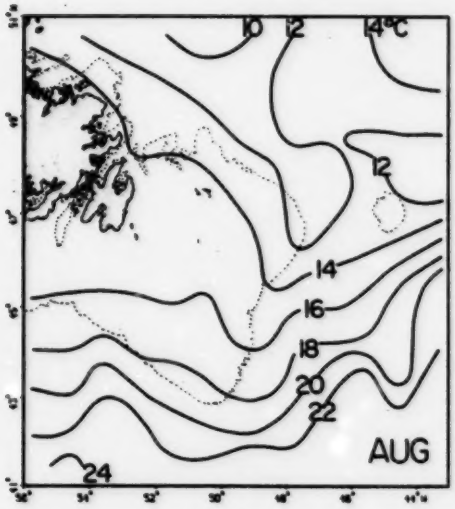
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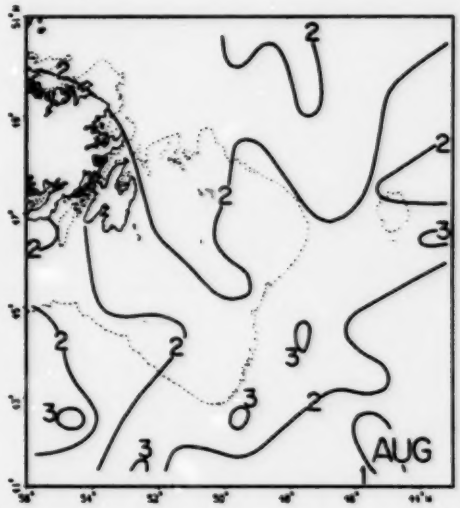
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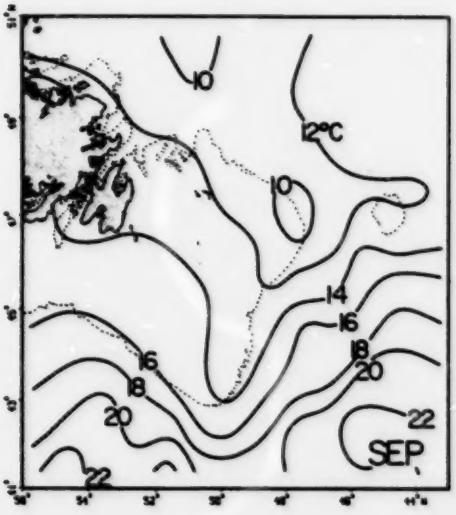
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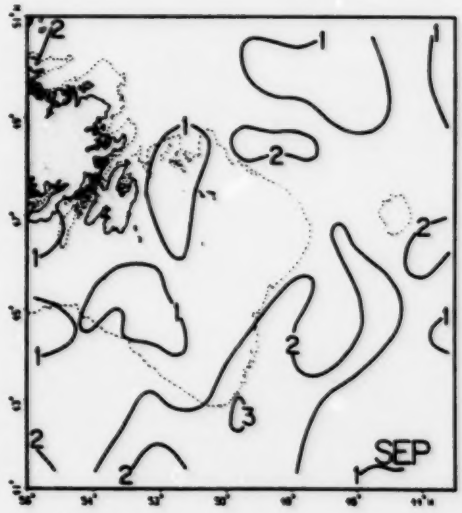
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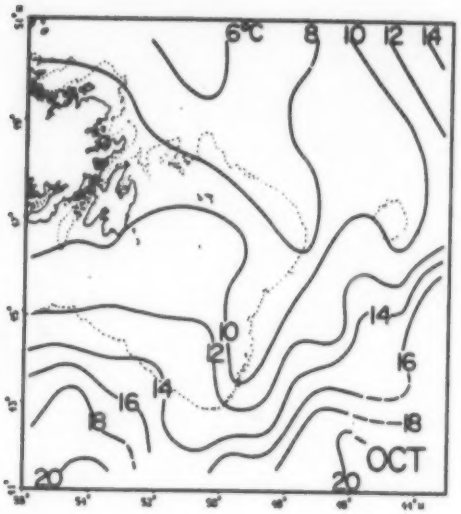
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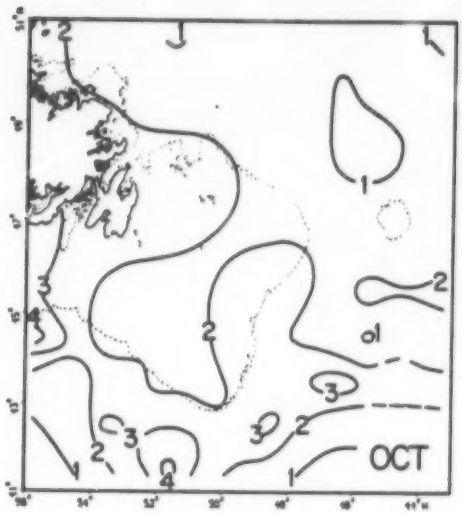
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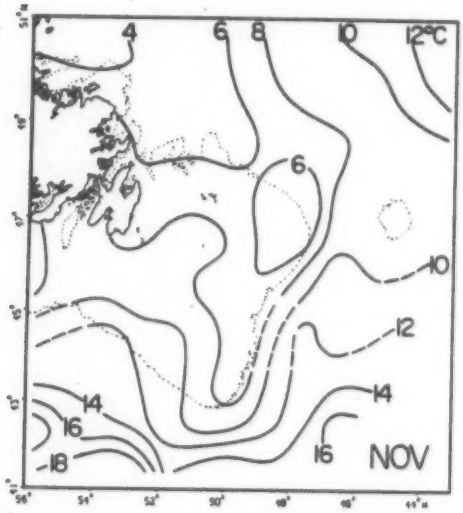
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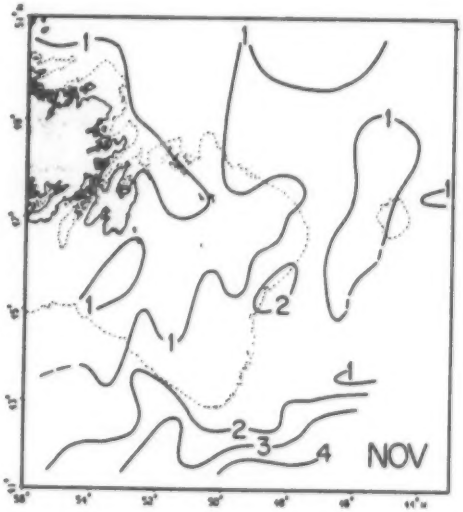
NOV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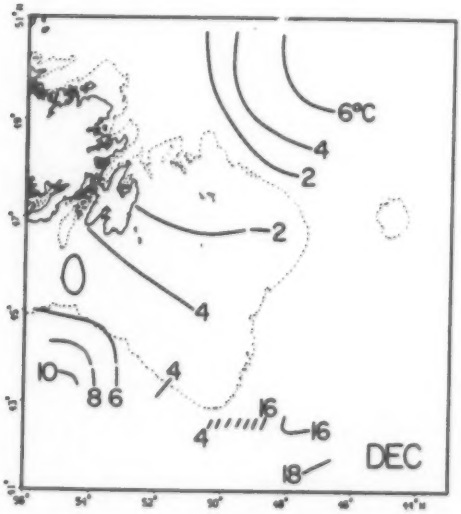
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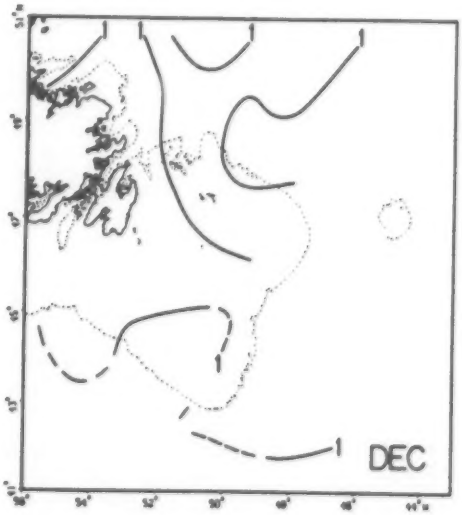
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